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16. ABSTRACT

A study was undertaken to determine which tree species can best maintain themselves in a landfill environment; to investigate the feasibility of preventing landfill gas from penetrating the root zone of selected species by using gas-barrier techniques; and to identify the (those) factor(s) which are most important in maintaining adequate plant growth on completed sanitary landfills. Ten replicates of nineteen woody species were planted on a ten-year old completed sanitary landfill and five gas-barrier systems were constructed. Of the nineteen species planted on the landfill, black gum proved most tolerant and honey locust least tolerant to anaerobic landfill conditions. Of the five gas-barrier systems tested, three proved effective in preventing penetration of gas into the root systems of the test species. Investigations into the effects of CO_2 and CH_4 contaminated soil indicated that red maple is more tolerant to the presence of these gases than is sugar maple.

An investigation of the effects of carbon dioxide (CO_2) and/or methane (CH_4) contaminated soil atmospheres on the growth of tomato plants indicated that CO_2 was toxic to tomato roots in a low O_2 soil atmosphere, whereas CH_4 was innocuous under the same conditions. No interaction was observed between CO_2 and CH_4 in terms of damage to tomato plants.

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Field and Laboratory Investigations

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August 1979

ADAPTING WOODY SPECIES AND PLANTING TECHNIQUES TO LANDFILL CONDITIONS

Field and Laboratory Investigations

by

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FOREWORD

The Environmental Protection Agency (EPA) was created because of increasing public and government concern about the dangers of pollution to the health and welfare of the American people. Noxious air, foul water and spoiled land are tragic testimony to the deterioration of our natural environment. The complexity of that environment and the interplay between its components require a concentrated and integrated attack on the problem.

Research and development is that necessary first step in problem solution and it involves defining the problem, measuring its impact, and searching for solutions. The Municipal Environmental Research Laboratory develops new and improved technology and systems for the prevention, treatment and management of wastewater and solid and hazardous waste pollution discharges from municipal and community sources, for the preservation and treatment of public drinking water supplies and to minimize the adverse economic, social, health, and aesthetic effects of pollution. This publication is one of the products of that research, a most vital communication's link between the researcher and the user community.

The ultimate use of refuse landfills involves the planting of vegetation. The problems of growing deep-rooted vegetation over former landfills has been studied through literature surveys, and greenhouse and field experiments. It was the purpose of these studies to gain an insight into the role of anaerobically produced gases (mainly methane and carbon dioxide) in curtailing the growth of plants on landfills. Methods of attenuating the detrimental effects of landfill gases were also evaluated.

Francis T. Mayo, Director
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Laboratory

ABSTRACT

During the past dozen years, many attempts to revegetate completed sanitary landfills have been undertaken throughout the United States, with variable degrees of success. This has been evaluated in a recent nationwide field survey of vegetation growth on completed sanitary landfills. Based on the results of this survey, literature reviews and other field experiences, a study was undertaken to determine which species, if any, can maintain themselves in a landfill environment; to investigate the feasibility of preventing landfill gas from penetrating the root zone of selected species by using gas-barrier techniques; and to identify the (those) factor(s) which are most important in maintaining adequate plant growth on completed sanitary landfills. Ten replicates of nineteen woody species were planted on a ten-year old completed sanitary landfill and five gas-barrier systems were constructed. The experiment was completely replicated on old forest land to act as a control. Of the nineteen species planted on the landfill for the past two years, certain species have tolerated the landfill conditions better than others. Black gum proved most tolerant and honey locust least tolerant to anaerobic landfill conditions. Of the five gas-barrier systems tested, plastic sheeting underlain by gravel and vented by means of vertical PVC pipes, a three foot mound underlain with one foot of clay, and a three foot mound with no clay barrier proved effective in preventing penetration of gas into the root systems of the test species.

Carbon dioxide and methane are the major components of sanitary refuse landfill-generated gas which has been associated with the demise of vegetation on and adjacent to completed landfills. An investigation of the effects of carbon dioxide (CO_2) and/or methane (CH_4) contaminated soil atmospheres on the growth of tomato plants indicated that CO_2 per se was toxic to tomato roots in a low O_2 soil atmosphere, whereas CH_4 per se was innocuous under the same conditions. No interaction was observed between CO_2 and CH_4 in terms of damage to tomato roots. Investigations into the effects of CO_2- and CH_4-contaminated soil indicated that red maple (Acer rubrum) is more tolerant to the presence of these gases than is sugar maple (Acer saccharum). With respect to gas concentration, 50% CH_4 alone in the root zone resulted in no visible symptoms whereas 20% CO_2 was found to cause adventitious root formation and visible decline in tomato shoots.

This report was submitted in fulfillment of Contract No. R 803762-02-3 by Rutgers University under the sponsorship of the United States Environmental Protection Agency. This report covers the period January 1, 1976 to September 14, 1978, and the work was completed as of October 15, 1978.

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SECTION 1

INTRODUCTION

The pressures of population expansion and urbanization have prompted a reappraisal of anticipated uses for completed landfill sites. Conversion to recreational areas or other non-structural usage has been considered an acceptable end for completed landfill sites in urban areas; and in rural areas intensifying land use has resulted in attempts to use completed landfills for growing commercial crops. Numerous farmers, as well as scores of landscapers, have encountered mixed success in trying to establish agricultural crops, trees, and shrubs on landfills throughout the country Three questions are often raised: "What species will thrive on completed landfill sites?", "Are there any techniques available which will help in attempting to establish a vegetative cover over a completed landfill area?", and "What is the nature of the toxic effect of landfill gas on vegetation?"

Reports from a nationwide mail survey funded by the Federal E.P.A. Solid and Hazardous Waste Division determined that the scope of problems encountered when vegetating completed landfills was indeed of national latitude. It was ascertained, from on-site visits to some 60 vegetated landfills, that answers to the previously raised questions would benefit not only the landscaper or farmer trying to vegetate a former landfill, but the general public as well in that they too would ultimately derive value from successful vegetation projects such as parks, golf courses and recreational areas.

In order to investigate the possibility of successfully growing vegetation on such areas, two experiments were designed: (1) a field experiment with three objectives: (a) to determine the relative tolerance of a number of commonly grown tree and shrub species to the soil environment created on and adjacent to a sanitary refuse landfill; (b) to determine if barriers to the migration of decompositional gases can function in preventing gas contamination of the root systems of selected sensitive species; (c) to identify those soil factors which are most responsible for causing vegetation growth problems on completed landfills. (2) A greenhouse experiment to assess the effects on vegetation of soil contamination by simulated landfill gas (CO_2 and CH_4) mixtures.

SECTION 2

CONCLUSIONS

1. Black gum, Norway spruce, and ginkgo were the three species most tolerant to conditions of the Edgeboro experimental landfill.

2. Honey locust, hybrid poplar, and weeping willow made the poorest growth of all surviving species on the landfill plot and appeared to be least adapted to landfill conditions.

3. Soil carbon dioxide, oxygen, moisture content, bulk density and temperature were important soil factors controlling the growth of American basswood on the experimental plot on the Edgeboro sanitary landfill.

4. Soil mounds, either with or without an underlying clay gas-barrier functioned successfully in preventing the migration of landfill gases into the root zone of trees. A 4-foot deep trench with a 1-foot layer of road gravel overlain with polyethylene sheeting and vented with perforated vertical vent pipes also functioned to keep out the gases of anaerobic decomposition.

5. Woody plants appeared able to better survive on a completed sanitary landfill if planted when small in height i.e. less than three feet. During this study, this factor appeared to be more important than the biological ability of a plant to withstand low oxygen environments.

6. Severe gas contamination of the original soil cover on the Edgeboro sanitary landfill was observed in isolated areas which could be located by the poor growth of vegetation associated with these areas. These soil gas conditions remained consistent for the fifteen month study period. The poor growth of vegetation in areas of landfill gas contamination was believed to be responsible for excessive erosion on the site.

7. Red maple (*Acer rubrum*), which is flood tolerant, was found to be more tolerant also of soil contaminated by simulated landfill gas than sugar maple (*Acer saccharum*) which is not tolerant of flooding.

8. Tomato plants growing in sand-solution greenhouse cultures were severely damaged by exposure to carbon dioxide concentrations of 17% or greater in the root zone. This response was not influenced by the presence or absence of high concentrations of methane or fluctuations in the O_2 concentrations, provided the O_2 in the root zone was not less than 2%.

9. Excessive concentrations of methane in the root zone of such tomato plants resulted in the depletion of oxygen, and the consequent decline of the plants after eight days' exposure.

10. Tomato plants exposed to excessive rhizosphere concentrations of carbon dioxide exhibited symptom development which differed significantly from that caused by lack of oxygen in the root zone, suggesting that high CO_2 concentrations damage tomato roots by a mechanism different from that of low oxygen concentration.

11. Rhododendron appeared to be poorly adapted to both landfill and control conditions.

SECTION 3

RECOMMENDATIONS

1. Those responsible for planting vegetation on completed landfills should avail themselves of current research on the adaptability of species to landfill conditions and avoid the use of non-tolerant species.

2. A survey of the landfill cover soil prior to establishing vegetation will help to avoid areas high in gas concentration for locating vegetation.

3. The use of a barrier technique for excluding landfill gas from the root zone of vegetation should be considered when planting on a former landfill. Two methods to consider would be (a) a mound of soil over the existing cover, (b) a lined and vented trench backfilled with suitable soil.

4. The use of smaller planting stock might also increase the chance of survivability.

5. Adequate irrigation of the plants established on a landfill is an important contribution to their survivability.

6. Special precautions should be taken to insure that the landfill cover soil has not been too densely compacted by heavy equipment. Loosening of the soil may be necessary before planting.

7. All cultural practices required for the successful establishment of vegetation in non-landfill soils should be considered, i.e. soil fertility, healthy planting stock, optimal soil density and physical characteristics, maintenance procedures, etc.

8. Further studies should be undertaken to determine if the ability to withstand high levels of carbon dioxide in the root zone is a characteristic of flood tolerant species.

9. The influence of secondary factors such as size of trees at planting, the use of bare-rooted versus containerized trees and the effect of water stress on the adaptability of species to landfill conditions should be evaluated.

10. The value of mycorrhizal fungi in inducing tolerance of trees to landfill conditions should be assessed.

SECTION 4

LITERATURE REVIEW

GAS PRODUCTION IN SANITARY REFUSE LANDFILLS

The serious disadvantages for adequate vegetation growth inherent in landfill sites; namely the production of toxic gas mixtures from anaerobic decomposition of organic matter present and leaching of infiltrates and gases into ground water supplies, as well as high ground temperatures, have been enumerated (32, 48, 160).

The composition of landfilled refuse varies considerably depending on its origin, be it municipal, industrial, incineration material or sewage sludge. The organic content of solid waste collected from homes, schools, commercial establishments and industries generally ranges from 50 to 75% on a weight basis. Most of these organics are biodegradable and can be broken down into simpler compounds by both aerobic and anaerobic organisms. The rate at which this occurs is reported to be a function of (a) permeability of cover material (b) depth of garbage (c) amount of rainfall (d) moisture content of the refuse. (e) putrescibility of the refuse (f) compaction (g) pH and (h) age of the landfill (i) redox potential (30, 87, 103, 138). The concentration of biocides as well as other factors may also effect the rate of decomposition.

When the refuse is initially deposited in the landfill, there is enough oxygen present to support a population of aerobic bacteria. This state lasts from one day to many months (49). The literature indicates carbon dioxide and water to be the principal products formed in aerobic decomposition (21).

After the oxygen concentration is depleted, the aerobic bacteria die, resulting in a sharp increase in the anaerobic bacterial population. During the anaerobic state of decompostion two phases have been identified, a non-methanogic state followed by a methane-producing stage (2).

During the non-methanogic stage, organic matter is reduced, in the presence of water and extracellular enzymes produced from bacteria, to smaller soluble components which include fatty acids, simple sugars, amino acids and other light--weight compounds (150). During the methanogenic stage, CO_2 and CH_4 are the principal gases produced. They originate from two reactions carried out by the bacterium Methano-bacterium (47).

Various other gases reportedly produced in the anaerobic environment of the landfill include ethane, propane, phosphine, hydrogen sulfide, nitrogen and nitrous oxide (3, 6, 14, 32, 96, 126, 150). Reserve Synthetic Fuel Company reports finding over 60 different gases in a California landfill (Frank Flower, Personal communication with Fred Rice, Reserve Synthetic Fuel Company March 15, 1977). Hydrogen sulfide which is produced from the bacterium Desulfovibrio desulfuricans in alkaline conditions (58), causes lower root respiration rates and a decrease in soil nematode population (84).

In addition to the methane-producing bacteria mentioned above, there exists a bacterium, Pseudomonas chromobacterium, which utlizes methane during its metabolism. It oxidizes methane, producing carbon dioxide and water (70). Since oxygen is required for this reaction, these bacteria will generally be found near the upper surface of the landfill.

During the oxidation of methane, oxygen is consumed. This raises a question of whether or not the oxygen concentration is a limiting factor in this reaction. Hoeks (70) points out that the organisms involved can function at soil atmospheric oxygen concentration as low as 1%. However, at this low concentration, incomplete oxidation causes formation of such intermediate side products as methanol, formaldehyde and formic acid (78).

Of the various factors influencing methane gas production, the parameters most commonly reported are refuse moisture content, temperature, oxygen and pH. Frequently the major factor is refuse moisture content. Ramaswamy (122) and Sougonuga (137) found that methane gas production rates increase with increased refuse moisture content, with a maximum production occurring at moisture content of 60 to 80% wet weight. Farquhar and Rovers (47) report maximum methane production when refuse is near the saturation point. An experiment carried out by Merz and Stone (99) concluded that methane gas production increased with the addition of surface irrigation water. Ludwig (94) found that at one of the two sites in California, methane production increased after a heavy rainfall. It is reported that refuse moisture content too low to support continuous gas production in a landfill may be in the range of 30 to 40% (99). This condition may exist in certain areas of the United States such as the dry southwest, where rainfall and relative humidity are very low.

Temperature has also been described as a limiting factor in the methane gas production. Kotze et al (82) report 37°C to be the optimum temperature for methane gas production in the mesophilic stage of sewage sludge decomposition. Dobson (37) and Ramaswamy (122) say maximum gas production occurs at 30°C and 35°C respectively. All found that deviations from the optimum temperature resulted in decreased methane production rates.

The optimum pH for methane production during anaerobic decomposition of sewage sludge is very near 7.0 (47). As deviations from this optimum are encountered, gas production is decreased. High pH may exist in the refuse because of the presence of alkaline materials. When methane production is inhibited, the information of organic acids results and the pH decreases (47).

EFFECT OF LANDFILL GASES ON PLANT GROWTH

Field Cases

Many reports of success or proposals for transforming barren former refuse sites into luxuriant vegetated areas have appeared in the literature and in the press (5, 12, 64, 88, 105).

In July 1972 an article by Duane (38) applauding the construction of golf courses on completed sanitary landfills cited the successful use of such tree species as Japanese black pine, London plane, thornless honey locust and Russian olive for beautifying the sites. In 1973, any anonymous article appeared in Solid Waste Management magazine describing the transformation "From Refuse Heap to Botanic Garden", of an 87-acre landfill in Los Angeles that the distinction of being one of the world's first such phenomena (4).

A catalogue published in 1973 describing hybrid poplars bred by a Pennsylvania nursery cites a particular hybrid which supposedly was grown successfully on a landfill site at Fort Dix, New Jersey (98). In that same year, a brochure was published by the Caterpillar Tractor Company describing and displaying in lavish color various successfully vegetated golf courses and parks in Mountain View, California; Anoka, Minnesota; Baltimore County, Maryland; Long Island, New York; Alton and Chicago, Illinois (24). In 1974 a news item in the Sun-Star of Merced, California described a 5-acre park whose new grass and trees would be aided in growth by "the proximity to the refuse which will provide needed nutrients" (6).

Few problems if any were either observed or anticipated in achieving these spectacular results with the exception of the report of root damage to large trees and shrubs at the Los Angeles Botanic Garden site.

At the same time, various investigators were experiencing difficulties in growing vegetation at similar sites. In January 1969, Professor F. Flower and associates of Rutgers University in New Brunswick, New Jersey (50), responding to a complaint of vegetation death on private properties adjacent to a landfill in Cherry Hill Township observed dead trees and shrubs of the following species: spruce, rhododendron, Japanese yew, azalea, dogwood, flowering peach, brush dogwood, Scotch broom, arbor vitae, Douglas fir, and lawn grasses. Testing of the soil with appropriate equipment disclosed high concentrations of carbon dioxide and explosive gases. The conclusion reached was that the trees and shrubs may have been killed by displacement of oxygen from their root zones by lateral movement of the gases of refuse decomposition or by the decomposition gases themselves.

In 1972, the Rutgers contingent made a visit to the peach orchard of the DeEugenio Brothers in Glassboro, New Jersey, which bordered on a completed landfill, where approximately 50 peach trees had died (51). Upon completion of the landfill, the growers had hoped to plant additional peach trees on the filled area. Examination of the soil atmosphere revealed high concentration of carbon dioxide and methane form the anaerobic decomposition of organic matter had moved laterally from the landfill into the orchard area.

The Hunter Farm, in Cinnaminson, New Jersey, was visited in December, 1974 when fields planted with rye were growing poorly (51). Gas checks revealed that combustible gases were present in the area of new vegetation injury and that migrating gases were traveling up to 600 feet from the nearest edge of the landfill.

Another trip to Hunter's Farm was made in June, 1975 when corn was found to be growing poorly in areas where combustible gas and CO_2 concentration were high.

On May 14, 1973, the Rutgers group visited Sharkey's Landfill in Parsippany-Troy Hills, New Jersey to estimate its potential for supporting vegetative cover and to examine field test plots set out by the county agent (53). It appeared that grass seeding had been attempted; however, grass seemed to be growing well over only small areas of the fill. Numerous pools of oily leachate were observed, many with gas bubbles breaking the surface.

Samples of soil gas revealed high concentrations of combustible gases. In the few areas where vegetation seemed to be growing well, there was little combustible gas in the root zone.

A communication from the county agent on June 3, 1975 reported that clover, vetch, lespedeza and weeping love grass were doing well on the landfill (79).

Although the literature on vegetation problems on completed landfills is fairly sparse, information received from a nationwide survey has indicated that such problems have been encountered throughout the United States. On-site visits (51, 52) to some of these areas in the northeast, the midwest, southern Alabama, the far west, Puerto Rico and southern California have corroborated the findings of the group at Rutgers University concerning the detrimental effect of landfill gases on vegetation atop or adjacent to completed sanitary refuse landfills.

The discrepancies in results of efforts to establish vegetation on former landfill sites is apparently due to variability in certain landfill characteristics such as type and amount of solid waste, depth and permeability of cover, construction and grading of the fill; certain meteorological conditions, such as temperature, relative humidity and rainfall, soil characteristics such as composition, texture, ability to retain moisture, nutritional characteristics; adaptability of plant species to landfill conditions, and planting and maintenance techniques to overcome unfavorable landfill conditions (17, 45, 123, 142, 154, 160).

Effect of Low Soil O_2 on Plant Growth

It has been known since the early 1900's that plants grown in solution culture required both air and minerals in order to achieve the best growth (44), this was found to be the case for barley, lupines (66, 127), and tomato (28, 41).

Chang and Loomis in 1945 (26) conducted a survey of the literature and found that although some plants could survive O_2 concentrations in the root zone as low as 1 to 2%, most plants would function normally at O_2 concentrations ranging from 5 to 10%.

There is a good deal of variability in tolerance to low O_2 in the root zone among different species of plants. The growth of red and black raspberries was inhibited by exposure to 10% O_2 (120), whereas apple trees required 10% O_2 in the soil in order to sustain growth (15). One-tenth percent O_2 in the flooded root zone of apple trees resulted in the death of the trees (15). Tomato plants grown in solution culture exhibited marked reduction in growth and ability to take up potassium when exposed to 3% O_2 in the root zone (153). Sour-orange seedlings in sand-solution culture given 1.5% O_2 in the root zone for seventeen weeks did not grow, and seedlings receiving 4.6 to 6.1% O_2 grew half as well as the controls (62). Rice plants have been reported to grow as well in solution culture having less than 1% O_2 in the root zone as control plants (153).

Aside from differences between species, environmental factors can also influence plant response to low O_2. High temperatures were found to increase the need for O_2 by growing root tips (120). A dense soil can also increase the need for O_2 by growing root tips. This is believed to be due to the extra energy required to push the root tips through the soil (61). The O_2 concentration in the soil is dependent on the ability of air to diffuse into and through the soil and the rate of diffusion is largely dependent on the texture and degree of compaction of the soil. Sandy soils generally exhibit ample gas exchange, whereas finely textured soils with pore spaces of less than 10% are prone to poor soil aeration (155, 161). Excessive compaction in soils containing large amounts of clay was found to result in O_2 concentrations of less than 2% and CO_2 concentrations as high as 20.5% (162).

Low concentrations of O_2 in the root zone can influence plants in ways other than by decreasing growth or killing the plants. Susceptibility of roots to soil-borne pathogens has been found to increase when the soil is poorly aerated. This is believed to be due in part to the ability of some pathogenic fungi and other organisms to flourish in such soils (8). Sustained low O_2 concentrations in the soil have been found to cause mineral deficiencies in plants. Potassium is the first mineral affected. The order in which the other major nutrients, nitrogen, phosphorus, calcium, and magnesium, become deficient depends upon the plant species (69, 78, 91).

Effect of High Soil CO_2 on Plant Growth

Carbon dioxide (CO_2) concentrations in the soil normally comprise less than 2% of the soil atmosphere. The death of vegetation in flooded or poorly aerated soils is not generally considered to be due to excessive CO_2 concentrations but rather to lack of oxygen (85). CO_2 concentrations as high as 20.5% have been reported in the soil under roadways and compacted paths in areas where trees were reported to have been killed, but the high CO_2 readings occurred in conjunction with very low O_2 concentrations (162).

In a sanitary landfill, the refuse is a source of CO_2 which can migrate into the surrounding soil, resulting in concentrations greater than 20% (52). The CO_2 migrating into the soil can displace the O_2, but not being dependent on the soil O_2 for its generation, it can occur in high concentrations in conjunction with O_2 concentrations which might not be considered limiting to plant growth.

Plant species vary in their sensitivity to excessive CO_2 in the root zone The exposure of plant roots to pure CO_2 was first shown to be toxic in 1914 (109). Pure CO_2 in soil around tomato and corn plants killed the plants after two weeks exposure (109). This was also found to be true for buckwheat which was killed after a few days' root exposure to pure CO_2 (56). The growth of guayule in solution culture exhibited a significant reduction (20), and red and black raspberries were killed when exposed to 10% CO_2 in the root zone (120). Cotton plants growing in solution culture exhibited optimum growth in the presence of 10% CO_2 in the root zone, provided at least 7.5% O_2 was also present. Thirty to 40% CO_2 in the root zone severely limited growth, and 60% CO_2 stopped growth of cotton completely (90). Tomato plants growing in solution culture exhibited a significant reduction in growth when exposed to 28% CO_2 for 24 hours, but were not inhibited by lower concentrations (44). Pea seedlings have been reported to exhibit a significant reduction in growth when exposed to only 1% CO_2 in the root zone (143) whereas barley plants growing in solution culture exhibited no reductio in growth when exposed to 20% CO_2 in the root zone (69). The roots of sour-orange seedlings growing in sand solution culture only ceased growing when exposed to 37.2% CO_2 (62).

Root growth of pea seedling has been reported to be stimulated by exposure to 0.5% CO_2 and inhibited by 1% CO_2 in the substrate (59, 143). The roots that were stimulated by exposure to low CO_2 concentrations were thinner and had an increased amount of lateral root initials. This stimulatory effect of low concentrations of CO_2 was attributed by the authors to the ability of the roots to use CO_2 as a carbon source (59, 116, 143). In light of more recent developments this stimulatory response is probably due to the CO_2 acting as an analogue to ethylene, competing for a receptor site in the cell. This competition would result in a hormonal imbalance that would manifest itself as a more pronounced auxin response (22, 25).

Valmis and Davis (53) investigated the mechanism by which CO_2 damages plant roots and demonstrated differences in sensitivity among plant species to exposure to CO_2 in the root zone. Tomato roots growing in solution culture exposed to pure CO_2 were killed immediately. The exposure of tomato roots under the same conditions to pure nitrogen resulted in a 90% reduction in the rate of growth. Rice plants were also killed by exposure to pure CO_2 in the root zone but exhibited no measurable reduction in rate of growth when exposed to pure nitrogen. Barley plants were killed by exposure to pure CO_2 and exhibited a 45% reduction in the rate of growth when exposed to pure nitrogen. This study shows that high CO_2 concentrations can kill plants by a mechanism other than lack of O_2. Norris et al (108), in 1959 postulated that the damage caused by CO_2 contamination in the root zone occurs when the CO_2 diffuses across the plasma membrane and disrupts the intercellular pH.

To summarize, carbon dioxide concentrations as low or lower than 10% in the root zone can be toxic to roots. Sensitivity of roots to CO_2 is species dependent. Concentrations of 60% or greater have been found to be toxic to all plants so exposed. The mechanism by which CO2 damages plant roots is not known, but the evidence indicates that it is not the same mechanism by which lack of O_2 damages plants.

Effect of Manufactured Gas on Plant Growth

Because it has been extensively studied as a phytotoxic gas when present in soil atmospheres, a review of the literature on the effects of manufactured gas could be enlightening.

The first reported incident of manufactured illuminating-gas damage to trees occurred on Pall Mall, London in 1807 after the first public street light system ever was installed (43). In the late 1800's and early 1900's a number of other researchers found that woody and herbacious plants were damaged by exposure to leaking manufactured-gas (83, 132, 140, 144).

Harvey and Rose (67) in 1915 reported that ethylene was one of the toxic components of manufactured gas. *Catalpa speciosa*, *Ailanthus altissima*, *Vicia faba*, and *Gleditsia* seedlings were divided into two treatments, one group exposed to illuminating gas and the other to ethylene. The seedlings responded in a similar manner to both treatments. Ethylene concentration in manufactured gas was usually high enough that leaks could be detected by placing tomato plants in the soil and making observations for epinastic curvature the next day (35). It has been shown that ethylene can be generated in concentrations which are biologically active in anaerobic soils (133).

Hitchcock et al (68), in 1934 reported that container-grown willow, cherry, maple and silver bell trees were severely injured when their roots were exposed to manufactured gas for 30 minutes. When cyanogen was removed from illuminating gas, 20 to 24 times more gas was required to cause injury to the trees. Cyanogen forms hydrocyanic acid when mixed with water and carbon dioxide. Cyanogen, as well as ethylene, has been considered to be largely responsible for the phytotoxicity of illuminating gas in soils. These compounds are not found in landfill gases or natural gas in concentrations nearly as high as in manufactured gas, if at all.

Effect of Natural Gas on Plant Growth

The composition of natural gas more closely resembles that of landfill gas than does manufactured gas (Table 1). The main difference between natural gas and landfill gas is that there is more CO_2 and less methane in the latter.

That natural gas can be toxic to plants was first noted by Schollenberger (131) in 1930, who found that plants were killed when the soil was saturated with natural gas, but that no permanent damage to the soil occurred. Exposing the aerial portions of plants to natural gas did not damage the vegetation (136).

Gustafson (65) in 1949 fumigated the roots of container-grown American elm trees during four consecutive growing seasons with concentrations of natural gas not exceeding 4%. Although slight discoloration of the roots was noted on the trees exposed to the gas, no injury to the shoots was reported.

Pirone (115) in 1960 reported that exposing the roots of tomato plants to pure natural gas for 48 hours did not cause any damage. The roots of Norway maples, London plane and pin oaks were fumigated with pure natural gas for 5 to 6 week periods at soil concentrations ranging from 60 to 100%. No damage to the trees was reported due to this treatment.

In 1972, Hoeks (70) reported that natural gas was responsible for the demise of 5 to 20% of the road trees in town centers in the Netherlands. He found that when soil was contaminated with natural gas for a period of time there was a build up of methane-utilizing bacteria whose activity resulted in the depletion of oxygen in the soil. The oxidation of methane follows the general equation ($CH_4 + 2O_2 = CO_2 + 2H_2O$ + Energy). The organisms responsible for this reaction belong to the *Pseudomonas* and *Chromobacteria* genera. Under experimental conditions the oxidation of methane was found to be so intensive that if O_2 was in excess all the CH_4 was depleted, and if CH_4 was in excess all the O_2 was utilized. This bacterial activity, in conjunction with simple displacement of the soil atmosphere by natural gas, was concluded by Hoeks to be responsible for the death of the many shade trees in the Netherlands.

Garner (58) in 1973 investigated the death of numerous shade trees near natural gas leaks in Wilmington, North Carolina, and concluded that the death of the trees was due to anaerobic soil conditions brought on by dilution of the soil atmosphere with natural gas and the activity of methane-utilizing bacteria. Garner also partially attributed the death of vegetation to the build up of hydrogen sulfide (H_2S) in the soil produced by *Disulfovibrio desulfuricans* under anaerobic conditions. He also reported extremely low soil nematode populations due to H_2S toxicity.

THE EFFECT OF SOIL FLOODING ON PLANT GROWTH

Soil saturated with landfill gases (52) or with water (86) often becomes anaerobic. The ability of a plant to survive in anaerobic soil is characteristic of flood tolerant species (61, 158). Such species, therefore, might prove adaptable to adverse growing conditions caused by refuse-generated gases on completed sanitary landfills.

Species vary considerably in their ability to withstand flooding due to a number of biological and environmental factors which are known to influence the ability of a tree species to survive in flooded soil. This is evident in the observable zonation of tree species on river banks, reservoir margins and bottom lands (19, 66, 74). Hardwood species are generally more tolerant of flooding than conifers (1, 61, 92). Soil type can also influence flood tolerance. In the U.S.S.R. on the Volga-Don flood plain *Populus alba*, *P.*

balamifera are recommended for clay-loam sites while *P. nigra* and *Acer negundo* are recommended for sand-silt sites (151). The time and duration of flooding are important considerations. Dormant trees are less sensitive to flooding than actively growing trees (66). Trees growing on the margins of reservoirs require that the site be flooded no more than 45% of the growing season in order to survive (66). In isolated years some species can tolerate flooding during the entire growing season (60). The condition of the flood water is another factor which may influence flood tolerance. Flooding with standing water is more injurious than flooding with moving water (129). Warm water can accelerate the death of trees exposed to flooding (19). If the flood water covers all or most of the trees above the ground, the tree is more likely to be injured than if only the soil is saturated (66). Older trees are generally more tolerant of flooding. This was found true both for hardwoods (80) and conifers (89).

In order for a species to survive flooding it must possess special characteristics that enable it to survive when the soil is anaerobic. Some species have the ability to undergo anaerobic respiration in the roots when flooded. Species which have been shown to do this are *Salix cinerea* and *Nyssa aquatica* (39, 72). The prolonged dependence upon anaerobic respiration can result in a build-up of toxic end products, such as ethanol, which can then become toxic to the plant (57, 76). Hook (72) has postulated that *Nyssa aquatica* can avoid being damaged in this way by producing secondary roots, thus increasing the size of the root system to compensate for the lack of efficiency and reducing the concentration of ethanol per unit tissue.

A large number of plants possess the ability to transport oxygen to their roots. This characteristic is associated with but not confined to flood-tolerant species. Corn, turnips, barley, carrot, lettuce, beets, leek, pea, onion, rye grass and cabbage (63) all have been shown to transport oxygen to their roots, but none of these species is considered flood-tolerant (72). This adaptation is more common in herbaceous species (61). Woody species, including *Populus petrowskyana*, *Salix alba*, *S. repens*, *S. atrocinerea* and *S. fragilus* have also been shown to transport oxygen to the roots. Lenticels on the stem were shown to contribute to this process (7, 27). Other woody species which can transport oxygen to their roots include *Fraxinus pennsylvanicum*, *Nyssa aquatica*, *N. sylvatica*, *Avicennia nitida*, *Picea abies*, *Liquidambar styraciflua*, *Liriodendron tulipfera*, and *Platanus occidentalis* (73). *Ananas comosus* (pineapple) can also transport oxygen to its roots. The gas moving to the roots was observed to contain up to 78% oxygen, most of which was believed to have been produced during photosynthesis (42).

The ability to develop adventitious and secondary roots has also been associated with flood tolerance (60). The original root systems of the flood-tolerant species *Fraxinus pennsylvanicum*, *Platanus occidentalis*, and *Nyssa aquatica* deteriorate when flooded, but secondary roots develop to replace them which are more succulent and less branched (71). Most flood-tolerant species develop adventitious roots at or below the water line (60). The adventitious roots of *Salix alba* can replace the original root system by growing in the sediment deposited by flood water (119). This could also be true for other species. It has been postulated that adventitious roots in flood water can carry on the salt-absorbing function while the damaged original root system continues to contribute to the water absorbing needs of the tree (85).

The ability to withstand elevated concentrations of CO_2 in the soil has been proposed as contributing to species ability to withstand flooding (72). This possibility has been neglected due to the generally accepted belief that low oxygen and not high CO_2 is the main cause of damage to roots in flooded soils (86). *Nyssa aquatica* seedlings are more tolerant of flooding and of high CO_2 concentrations in the root zone than *Liquidambar straciflua*. *N. aquatica* was not affected by exposure to 2 or 10% CO_2 in the root zone for up to 15 days, whereas 30% CO_2 over the same period retarded root and shoot development and decreased the rate of transpiration. *L. styraciflua* exhibited chlorosis when exposed to 2% and was killed by exposure to 10 to 30% CO_2 for 15 days (71).

The exact nature of the flood-tolerance mechanism for any species has not been determined. There could be contributing mechanisms other than the ones discussed above. The work done indicates that a combination of adaptations can be responsible for flood tolerance. *Nyssa aquatica* is tolerant of high CO_2 concentrations in the soil, it can undergo anaerobic respiration, it develops adventitious and secondary roots and it can transport oxygen to the roots. All these adaptations are believed to contribute to its tolerance of flooding (72). The ability of five hardwood trees to tolerate flooding was found to correspond to their ability to transport O_2 to the roots, develop adventitious roots and undergo anaerobic respiration. The more flood tolerant the tree, the more developed were these adaptations. The trees in order of increasing flood tolerance were *Liriodendron tulipifera*, *Liquidambar styraciflua*, *Platanus occidentalis*, *Fraxinus pennsylvanica* and *Nyssa aquatica* (71).

The mechanisms which enable a species to adapt to flooding have evolved in response to flooding. The conditions on a sanitary landfill may resemble flooding in terms of anaerobic soil conditions but there are significant differences between the two environments, the most dramatic departure being the lack of water on the landfills. Most flood tolerant species develop adventitious roots which would not be able to develop under landfill conditions due to the lack of water. It is not known to what extent these roots contribute to flood tolerance. It has been postulated that adventitious roots develop in response to a build-up of growth regulators and carbohydrates at the base of the stem and are a response rather than adaptation to flooding (84). Anaerobic soil conditions could be more stable on a landfill than during flooding and not give the trees a chance to grow at all. The ability to withstand high concentrations of CO_2 in the soil might be more important on a landfill where the concentrations of CO_2 in the soil can exceed 40% (52).

EFFECT OF OTHER SOIL PARAMETERS ON PLANT GROWTH

Soil Temperature

A number of investigators have characterized the optimum temperature for root growth of some selected species. As early as the 19th century, King found that corn roots responded quite differently to different soil temperatures throughout the growing season (77). Early in the season, cooler soil temperatures promoted more horizontal root growth than later in the season when higher soil temperatures caused the roots to respond by growing vertically. Burstrom (23) in 1936, found that total growth in length of wheat roots is optimum at temperatures around 68°F and decreases at temperatures above and below this optimum. Richardson (124) described a similar relationship for silver maple (Acer saccharinum). Soil temperatures of 68°F were reported by Rufelt (128) as optimum for maximum growth of wheat plants. The tops of oats generally grow better at 70°F and the roots at 60°F indicating a difference in the optimum temperature for root and shoot growth, respectively.

Total dry weights of both roots and shoots are influenced by the temperature of the root zone. Maximum dry weight of wheat plants increased with decreasing temperatures from 86°F to 50°F, whereas optimum growth of rye grass tops occurred at 67°F with growth decreasing as the temperature was raised to 82°F or lowered to 52°F (107). This same temperature range has been reported for barley (118), rye grass (110), corn, bromegrass (106), oats, tobacco (111), and tomato tops (34). The root growth of wheat and other species was found to be optimum at about 68°F whereas Italian rye grass roots grew best at 52°F (106).

Moisture Stress

Because of their perennial nature, long life, and potentially large size, trees require special consideration in the study of their growth and development under environmental stress. For example, water stresses during several separate growing seasons may affect each year's growth increment and thus, the effect of a given water stress is different in a tree seedling than in a mature tree. Drought during a critical period one year may result in reduced food storage for utilization in growth the following year, and the effect on development of wood tissue or of flowers and fruits can be appreciable for several succeeding years. The root/shoot ratio may be seriously affected by water deficits in woody seedlings, whereas in large trees the more important effect of the same deficits may be in the distribution of growth along the annual sheath of wood.

There is convincing indirect evidence that shoot growth in trees is related to water stress. Forest mensurationists find tree height the most sensitive growth parameter for measuring site productivity, to which the generally accepted key is soil moisture (121, 141, 159). Correlations between rainfall and shoot growth have been attempted with various degrees of success for many decades (102, 113), but there is little doubt that longer shoots are produced in wet years than in dry years by many tree species on upland sites. Root tissues are probably never at as severe water stress as shoot tissue because of the time lag in the build up of water tension between the transpiring leaf and the absorbing root.

Soil water stress reduces the number, rate of expansion, and final size of leaves. In species whose entire leaf crop for one year is present as preformed primordia in the overwintering bud, water stresses of the preceding year regulate the numbers of leaf primordia that form in the developing bud

(40, 81). In these species, e.g. Pinus strobus, water stress during the period of shoot growth has no significant effect on the numbers of leaves that mature, but results in smaller leaves spaced closer together and ultimately less leaf weight (93). Clemments (29) found that numbers of needle fascicles on current shoots of 20-and 5-year old Pinus resinosa were directly proportional to the frequency of irrigation during the previous growing season. Therefore, it can be concluded that the previous year's deficits may affect tree species whose leaf primordia are all preformed in the overwintering bud by reducing leaf numbers, and that current year deficits may reduce the size of leaves and their spacing along the shoots. In other species e.g. Pinus taeda, which can add new foliage throughout the growing season, not all leaf primordia are preformed in overwintering buds, so water deficits during the season of flushing probably reduce production as much as deficits of the previous season (163). Zahner (163) showed that for sapling-size Pinus taeda grown outdoors in large containers, the 2-year effect on elongation of the terminal leader of well-watered trees was almost twice that of trees subjected to extreme drought conditions.

Lotan and Zahner (93) measured elongating needles on 20-year old Pinus resinosa trees under conditions of imposed drought and irrigation. Needles on the irrigated trees expanded for several weeks longer, at a 30% faster rate, and reached a 40% greater length than needles of trees under the drought treatment.

Root growth is also adversely affected by soil moisture stress. Two studies have emphasized that resistance increases sharply as the soil dries, and the resulting physical impedence of penetration by a root tip is considered a limiting factor independent of the deficiency of water for absorption (10, 148). Therefore, the failure of roots to grow into dry soil is probably more the result of physical impedence than of soil water stress. However, cambial growth continues slowly in dry soil because dry soil should not appreciably affect secondary growth (81).

EFFECT OF SOIL PARAMETERS ON SOIL PROPERTIES

Soil Temperature

The processes of ammonification and nitrification in soil are among those affected by soil temperature (128, 157). A temperature between 77°F and 99°F was found to be optimum for the activities of the nitrifying bacteria (147, 156); above 130°F and below 45°F the nitrification rate was severely reduced (156). Ammonification requires a higher optimum temperature (104°F) and the bacteria responsible can remain active at higher temperatures than the nitrifying bacteria. Frederick (55) and Sabey (130) studied nitrification in greenhouse pots of soil without plants. Both corroborated the results of the previous investigators in that higher rates of nitrification were associated with increasing temperatures (from 36°F to 95°F and from 32°F to 86°F, respectively) and that nitrate formation was entirely inhibited at temperatures of 104°F (147, 156).

Low O_2 Tension

Several investigators have found that oxygen concentration in the soil strongly influences the fate of many soil components by altering soil reactions and finally affecting plant growth.

Ponnamperuma (117) has reviewed a large quantity of the literature concerning the dynamics of flooded soils i.e. soils low in oxygen concentration. It is common knowledge that the moment a soil is flooded, its oxygen supply is virtually cut off. Oxygen can enter the soil only by molecular diffusion (which is 10,000 times slower than in the absence of water) (71) or by diffusion of gaseous oxygen through plants from aerial parts through aerenchyma cells continuous with the roots.

When the oxygen supply to the soil is cut off, aerobic organisms quickly deplete the oxygen remaining in the soil and become quiescent or die. The facultative anaerobes, followed by the obligatory anaerobic organisms, then take over the decomposition of soil organic matter; using oxidized soil components such as nitrate, manganic oxides, ferric oxides, sulfate, or phosphate; or dissimilation products of organic matter as electron acceptors in respiration.

Nitrate is the first soil component to undergo extensive reduction when oxygen becomes limited (117). Although it is known that nitrate reduction (denitrification) often occurs in slight amounts in well-aerated soils at optimum moisture level, the percentage of nitrate lost is usually not significant until the oxygen concentration is 12% or lower. A concentration of 0.46% oxygen resulted in comparatively large nitrate losses through denitrification (18).

Almost coincident with denitrification is the reduction of the higher oxides of manganese (MnO_2, Mn_2O_3, Mn_3O_4), because of their similarity to nitrates with respect to redox potential in flooded soils. The reduction may result from these compounds functioning as either (a) electron acceptors in the respiration of microorganisms or (b) chemical oxidants (95). Reduction of the oxidized forms of manganese causes an increase in soluble or manganous-manganese in the soil solution.

The next soil constituent to be reduced in the thermodynamic sequence is $Fe(OH)_2$. This reduction process operates at a considerably lower redox potential than that required for the two previously mentioned compounds (31). The process releases soluble or ferrous iron into the soil solution which can then be taken up by plants or complexed with other molecules.

The reduction of sulfate to sulfide occurs only when the soil has undergone appreciable reduction i.e. when the redox potential has fallen to a very low value (46). However, in soils high in iron, the likelihood of H_2S toxicity to plant roots is minimal because of the formation of insoluble FeS.

ESTABLISHING VEGETATION ON LANDFILLS

Cremer (33), in 1972, planted seedlings of four species of pine in a simulated sanitary landfill wherein raw refuse was placed in steel containers on top of which was placed two feet of soil. After one year the seedlings in these containers were growing as well as the controls.

More, Molze and Browning (101), in 1974, proposed that transpiration by vegetation can reduce the amount of leachate escaping from a landfill. Their study was conducted in a lysimeter designed to simulate landfill conditions. Raw refuse was interspaced with soil in the lysimeter and two feet of soil placed on top. Four woody species were then placed in the lysimeter: silverberry (Elaeganus pungens), black locust (Robinia pseudoacacia), bristly locust (Robinia hispida), and slash pine (Pinus elliottii). All these species grew well in the simulated landfill and were able to reduce the amount of water leached from the modified lysimeters. The roots of the plants grew through the refuse and no methane was reported to have been produced in the lysimeters, indicating that anaerobic conditions did not occur in this simulated sanitary landfill.

Such systems in which small amounts of refuse are placed in containers (lysimeter) do not reproduce true landfill conditions. The small amounts of refuse used cannot duplicate the temperature, gas production or settlement generated by the large quantities of refuse that occur in real landfills.

Swope (146) in 1975, conducted a survey of 24 completed landfills in the state of Pennsylvania. He concluded that 19 of the 24 landfills had vegetative cover inadequate to prevent erosion. Considering only the seeded portions of the nineteen revegetated landfills, twelve were observed to have cover inadequate to prevent erosion. Of five landfills on which no attempts had been made to establish vegetation, four were judged to have a cover of volunteer vegetation inadequate to prevent erosion. The physical soil characteristics most often found limiting to vegetative growth were: low soil fertility, droughtiness, high percentage of course fragments in the soil, slope, and lack of adequate soil cover. The effects of landfill gas contamination of the soil were not examined.

There have been numerous attempts to establish trees and other forms of vegetation on completed sanitary landfills (52). These attempts unfortunately were not designed as controlled experiments. In a national survey, Flower et al (52), examined a number of completed sanitary landfills and reported that problems with the establishment of vegetation included: lack of soil cover, droughty conditions, poor quality cover material, poor planting practices, lack of care, and landfill gas contamination of the soil. In many instances there was a strong direct correlation between the poor growth of vegetation and the occurrence of landfill gases in the soil. Symptoms exhibited by woody species exposed to landfill gas contamination were: a general lack of vigor, dieback, scorching of the leaves or needles, and rapid death. The death of vegetation on or adjacent to landfills caused by landfill gases has also been reported in Japan (152), and Canada (6).

SECTION 5

EXPERIMENTAL PROCEDURES

FIELD STUDIES

Selection of Appropriate Site for Landfill Vegetation Field Study

An ideal site for the species screening and gas-barrier technique study was defined as one which has a relatively high combustible gas concentration and adequate drainage. The control site should be located on virgin land, close to, but not adjacent to the landfill and have no combustible gas in its soil atmosphere. The sites should be large enough to accommodate a four foot spacing between adjacent trees.

An appropriate site for the experiment was located on the tidal marsh of the Raritan River in East Brunswick, New Jersey a distance of about two miles from the Cook Campus (Figure 1). The site had been operated as a landfill since the early-1960's by the Herbert Sand Company which offered space on the landfill and space on a nearby undisturbed tract of land for the experimental and control plots respectively.

Adjacent to the southern boundary of the landfill is a woodlot. This was an island used as a defensive position by colonial forces during the Revolution. All other landfill boundaries are tidal creeks that flow into the Raritan River or other landfills located over marshland.

The geologic history of this area is Atlantic Coastal Plain with the Piedmont Plateau boundary less than one mile to the North and West. According to Patrick et al (112), the soil would be sassafras loam or sandy loam with a sand deposit that is quarried on the southern side of the woodlot. The soil covering the landfill seems to be a sassafras subsoil as indicated by the presence of quartz and other stones with a reddish-yellow to yellow-brown tint (149).

Characterization of Vegetation on Edgeboro Landfill

In order to evaluate the degree of change imposed on the area by our experimental plantings, we first characterized volunteer vegetation in the area. For the most part the work in surveying the native vegetation was accomplished with a minimum of equipment (36). The mapping was performed by use of a hand-held compass, and the distances were measured by pacing on the landfill and by the use of a wheeled odometer on the woodlot. The bearings and distances measured were placed on graph paper to show the respective outlines of the two areas studied. Plotting the map on graph paper helped in determining the area by the formula using a coordinate system.

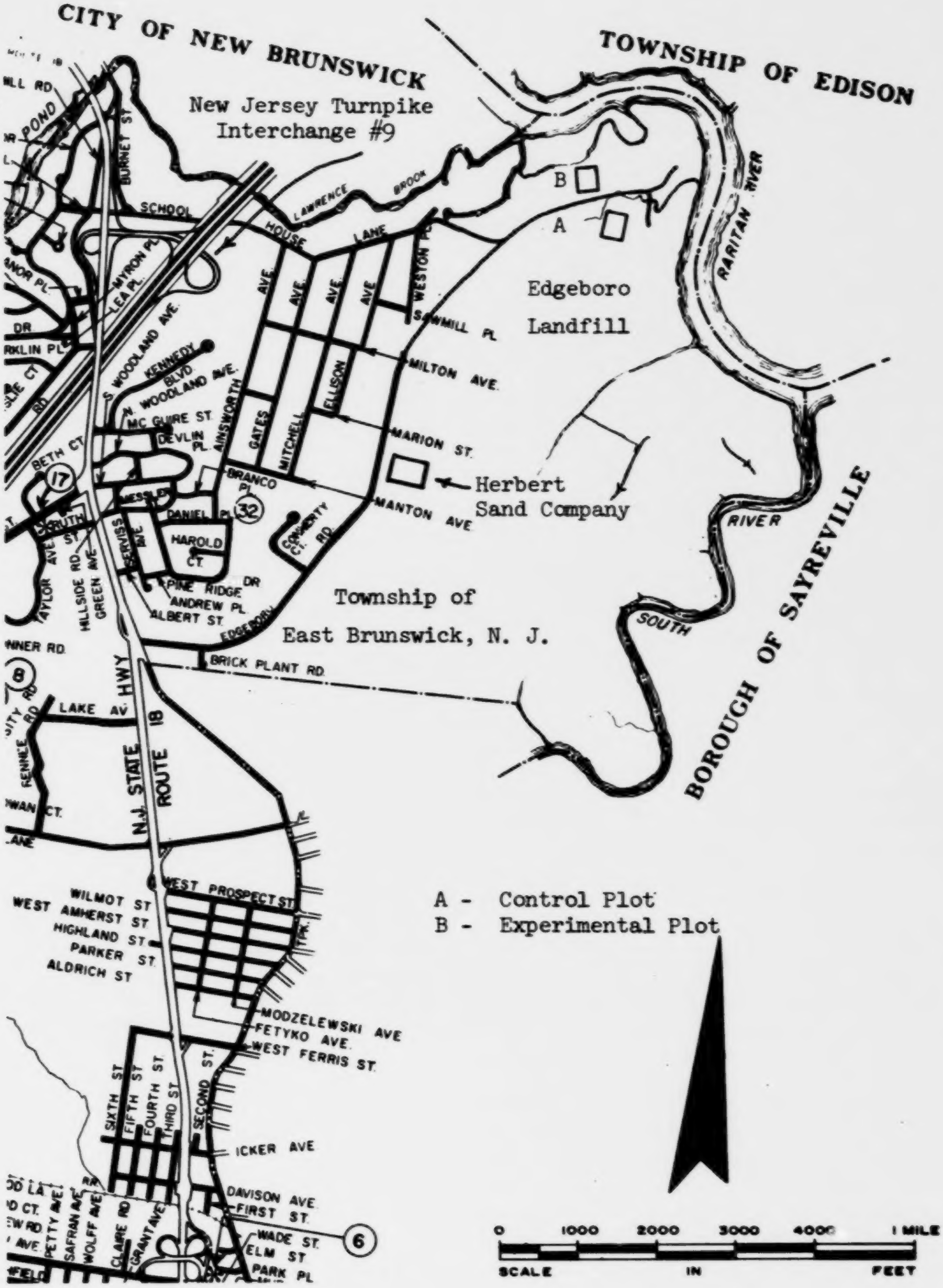

CITY OF NEW BRUNSWICK
TOWNSHIP OF EDISON
New Jersey Turnpike Interchange #9
LAWRENCE BROOK
RARITAN RIVER
B
A
Edgeboro Landfill
Herbert Sand Company
Township of East Brunswick, N. J.
SOUTH RIVER
BOROUGH OF SAYREVILLE
SCHOOL HOUSE LANE
MILTON AVE.
MARION ST.
MANTON AVE
BRICK PLANT RD
N.J. STATE HWY ROUTE 18
WEST PROSPECT ST
A - Control Plot
B - Experimental Plot
0 1000 2000 3000 4000 1 MILE
SCALE IN FEET

Figure 1. Location of landfill vegetation growth experiment, East Brunswick, New Jersey

$$2(\text{Area}) = Y_a(X_b - X_n) + Y_b(X_c - X_a) + \ldots\ Y_n(X_a - X_{n-1})\ (104).$$

Twenty-five randomly stratified plots, 50x50 feet, were used to determine the composition and successional changes in the woodlot (Figure 2). In each plot, the DBH (diameter at breast height, 4½ feet) of all trees over two and one-half inches was recorded with the use of a 24-inch tree caliper. In the case of one sassafras tree a metric biltmore stick graduated at two centimeter intervals was used and the result converted to the English system. The shrub layer was measured by the number of stems in a plot.

On the landfill, stems of all woody species were counted since only three trees were above the minimum stem DBH of two and one-half inches. As a check to note the effectiveness of the woodlot as a seed source, the number of stems on each side of the road dividing the landfill approximately in half from the southwest corner to the northeast corner was determined.

Unfilled Island Vegetation--

The island was divided into nine different regions that are at varying stages of succession or are dominated by a defined cover type (Figure 2).

1) Grass and rose stage - Here the dominant species are *Andropogon virginicus*, *Phragmites australis* and *Rosa spp*. Over most of the area *Andropogon* is dominant except where the moisture seems to collect, and here *Phragmites* will tend to be dominant. Different species of wild roses come up through these grasses and tend to prepare the soil for the next stage of development.

2) Bayberry-smooth sumac stage - The roses give way to a thick shrub cover of bayberry (*Myrica pensylvanica*) and smooth sumac (*Rhus glabra*). Seedlings of black cherry (*Prunus serotina*) and black gum (*Nyssa sylvatica*) appear through this canopy starting the succession toward a forest cover type. Arrowwood viburnum (*Viburnum dentatum*) acts as an understory to both sumac and bayberry, but eventually replaces the latter as the dominant shrub while the former attempts to become the canopy species.

3) Smooth sumac-black cherry-sassafras stage - A tree canopy becomes established with sumac and cherry predominating and sassafras (*Sassafras albidium*) advancing as a challenger for the dominant position. Smooth sumac has to be considered a tree species here since it reaches 20 feet in height and a maximum of 5½ inches DBH. Black gum is co-dominant to the other three species while the major understory species is flowering dogwood (*Cornus florida*). Bayberry is still present in the shrub layer, but is losing fast to the Arrowwood viburnum under a closed canopy. A small number of red maple (*Acer rubrum*) are associated, but never become more than an associated co-dominant species.

4) Black cherry-sassafras-black gum stage - This stage is more or less the same as the previous stage, but smooth sumac has dropped out from competition and oak-hickory regeneration has started. The shrub layer is dominated by arrowwood and the understory by flowering dogwood. After this stage the succession will go to oak-hickory or to sassafras if it can regenerate

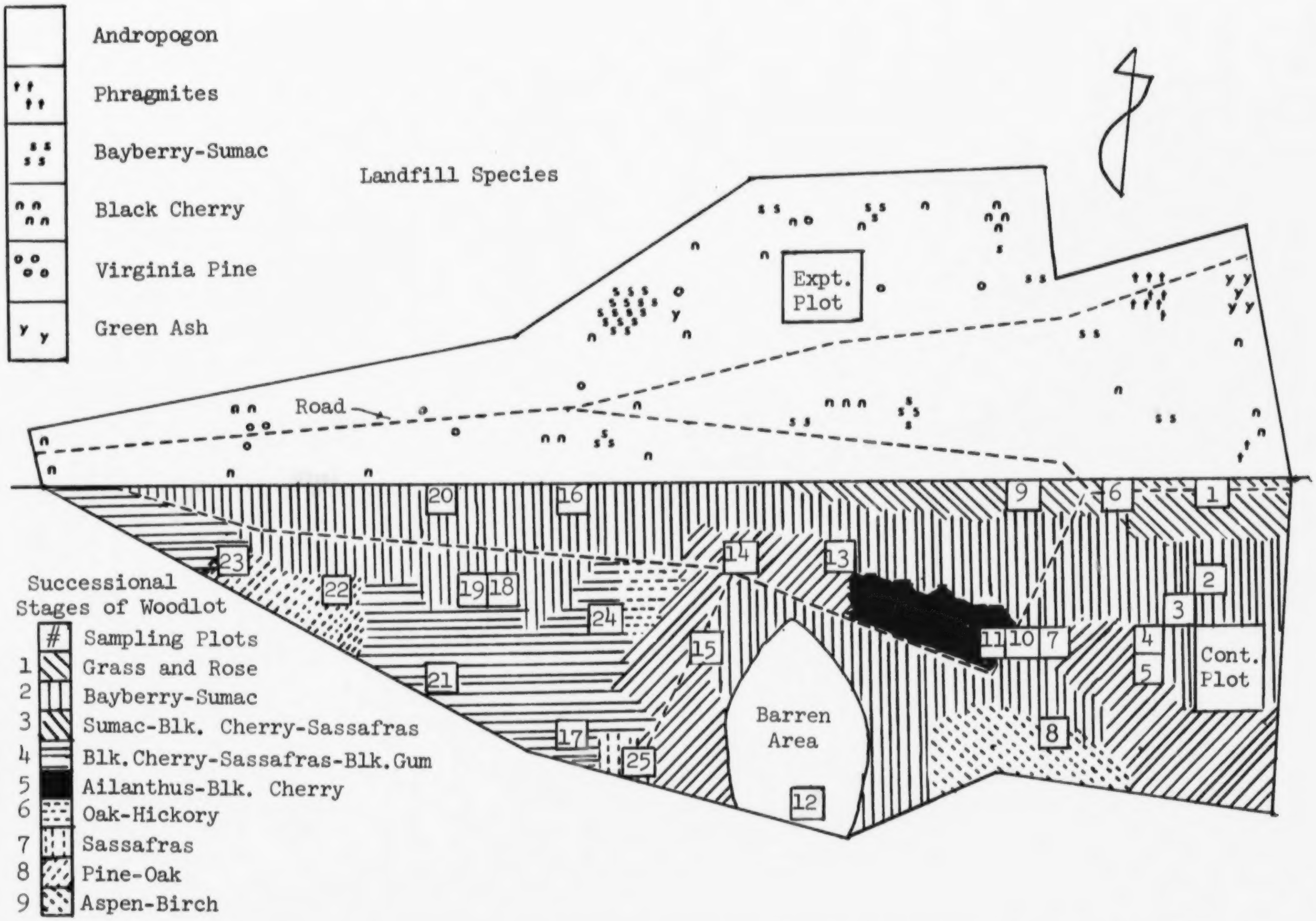

Andropogon
Phragmites
Bayberry-Sumac
Black Cherry
Virginia Pine
Green Ash
Landfill Species
Expt. Plot
Road
Successional Stages of Woodlot
# Sampling Plots
1 Grass and Rose
2 Bayberry-Sumac
3 Sumac-Blk. Cherry-Sassafras
4 Blk.Cherry-Sassafras-Blk.Gum
5 Ailanthus-Blk. Cherry
6 Oak-Hickory
7 Sassafras
8 Pine-Oak
9 Aspen-Birch
Barren Area
Cont. Plot
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25

Figure 2. Species distribution on landfill and successional stages on adjoining woodlot.

vigorously.

5) Ailanthus-black cherry stage - Ailanthus (Ailanthus altissima) replaced smooth sumac earlier in the succession and becomes the dominant species with black cherry co-dominating. The succession seems to follow the same sequence as from stage 3), the only exception being that Ailanthus will take longer to succumb to the more tolerant species so that oak-hickory regeneration will occur while it is still present in the canopy.

6) Oak-hickory stage - This type resembles Type 40 (Post Oak-Black Oak) of the Society of American Foresters (54). Black oak (Quercus velutina) and bitternut hickory (Carya cordiformis) are the dominate canopy trees with black gum, post oak (Quercus stellata), sassafras and black cherry in the co-dominate position.

7) Sassafras stage - An allelopathic substance from the leaves of sassafras inhibits the regeneration of other species and a stand is produced that will be mono-species in content for a long part of its life. The regeneration of sassafras under its own canopy is slow to non-existent in older stands. The stand in the woodlot has the largest tree present, 33 inches DBH, plus two others over 20 inches DBH. This is S.A.F. Type 64 (54).

8) Pine-oak stage - This is a Society of American Foresters (S.A.F.) Type 76 (54) with Virginia pine (Pinus virginiana) dominant with advance oak regeneration of post oak, black oak, blackjack oak (Quercus marilandica), and pin oak (Quercus palustris) as the rising co-dominant species (97). Red maple is associated with this cover type and would seem to take a secondary position with black gum to the species mentioned above.

9) Aspen-birch stage - Although this is an earlier transition form, it is not the dominate form on the north side of the woodlot. On the south side this quaking aspen-grey birch variation of S.A.F. Type 19 (54) has a much higher coverage. Quaking aspen (Populus tremuloides) and grey birch (Betula populifolia) form the dominate cover of this area with a shrub layer changing from bayberry to arrowwood. The associated species are black gum and Malus spp., the latter is either a domestic apple or one of the types of wild crabapples.

Landfill Vegetation--

The landfill itself is still too early in succession to designate a forest cover type or one that may be emerging, so three areas of examination were conducted: the ground cover, the shrub layer and the arborescent vegetation that is developing.

1) Ground cover - This is very similar to stage one in the woodlot, Andropogon is predominant with Phragmites localized. Trailing strawberry (Euonymus obvatus) and greenbriar (Smilax rotundifolia) crisscross the open areas with the former being the only live vegetation over the gas upwellings when it sends a stolon from one side of the gas area to the other.

2) Shrub layer - Bayberry and smooth sumac are the predominant shrubs, forming pure patches in localized areas scattered over the landfill. Not as

numerous, but still present are the wild roses and the *Malus spp.* found as scattered bushes over the area. Found now in greater numbers or for the first time, are the black haw (*Viburnum prunifolium*), highbush blueberry (*Vaccinium corymbossa*) and witch hazel (*Hamamelis virginiana*), probably from the Raritan River Flood Plain, which represents another seed source influencing the landfill site. These occur as scattered bushes for the most part.

3a) Arborescent vegetation, north side - Black cherry is very numerous, being about six times as numerous as ailanthus, black gum, and red maple. Lesser amounts of pin oak, sweet gum (*Liquid-ambar styraciflua*), boxelder (*Acer negundo*), green ash (*Fraxinus pennsylvanica*), and cottonwood (*Populus deltoides*), again probably from the flood plain, were found with the usual old-field species grey birch, eastern redcedar (*Juniperus virginiana*), shortleaf pine, sassafras, and black locust (*Robinia pseudoacacia*). Most of the tree forms occur on the edge of the landfill where there is probably more soil and less refuse. Absence of any gas upwelling seems to be responsible for the growth of most, if not all, these trees.

3b) Aborescent vegetation, south side - The area here is greater than that on the north side of the road, but the vegetation is sparser. The numbers of black cherry are about one-third less than on the other side, but it is still the most numerous species found. A small grove of green ash is found on the northeastern corner of this section, near a patch of *Phragmites*, numbering about two-thirds the amount of black cherry found here. Associated with the green ash are boxelder, and honeylocust (*Gleditsia triacanthos*), again species found on river bottoms. The rest of the species found in reducing frequency are eastern redcedar, grey birch, red maple, sassafras, ailanthus, shortleaf pine, black gum, and quaking aspen, all of which are found in the woodlot.

Discussion--

At first the flood plain was not considered a major seed source, but because of the prevailing winds from the northwest and the large numbers of birds and rodents from the flood plain visiting the landfill, a reversal in thinking occurred after the data were collected. The prevailing winds work against the woodlot as a source of windblown seed as shown by the low number of shortleaf pine seedlings. The seedlings of pine found on the landfill showed a distribution pattern emanating from the southwest. When the winds are from this direction they blow through the pine stand. The flood plain is then the major source of wind-blown seeds while probably equal to the woodlot as a source of animal-borne seeds.

The presence of two seed sources will show a different trend than that seen in the woodlot. This greater number of species may be an added benefit since a greater variety of responses of more trees can be seen than if there were but one seed source.

Any trend now seen on the landfill would be superficial, since major root competition is just beginning to occur in the soil. The soil depth varies on the landfill from the edges where more soil is usually found to the areas of gas upwellings that have been eroded by the wind to expose the refuse. Billings (13) states that Virginia pine has most (56-64%) of its root system in the top 6 inches of soil, while oaks and other more tolerant species tend to have deeper root systems. The distribution of roots into the deeper portions of soil increases with time over the life of the stand. The next ten to twenty years will be the true test of this natural vegetation to see whether the roots do penetrate the refuse or if the refuse acts as a barrier and prevents penetration. The result may then be an edaphic climax or a constant shifting of types until no gas exists in the soil. Roots often have the habit when possible, to circumvent a barrier and send roots to areas more favorable, as shown by Stout (145). One Virginia pine in particular, found growing on the landfill was checked for the presence of mycorrhizal fungi after a basidiocarp was found adjacent to it. The fungus was not identified, but the pattern of the tree roots was striking. A lateral root from the sapling grew out of the north side of the tree and swung clockwise around the tree until it found a path to a better soil condition marked by increased vegetation. On the eastern and western sides of the tree, areas of gas upwelling were found. A second pine in a similar situation had very poor form and vigor, and a check of the roots showed an absence of mycorrhizal fungi and a compact root system.

Final Evaluation--

Vegetation succession on the landfill is still in the very early stages of tree growth (9, 100). Patterns are not occurring too far out of sequence even though the number of trees may be high for the age of abandonment (eleven years). A study of the patterns of root growth of these trees could be quite useful in understanding the problems that occur in establishing plantings on landfills. Coupled with these observations mycorrhizal fungi could be evaluated for their help in relieving vegetation stresses that occur here. Table 1 summarizes the main species found on the Edgeboro Landfill site and adjacent island.

TABLE 1. TREE DISTRIBUTION AND DENSITY - EDGEBORO LANDFILL AND ISLAND

Species	Number Found On Landfill North Section	South Section	Also Present In Woodlot	Test Plot
Acer rubrum	15	3	X	X
Acer negundo	1	2	-	-
Ailanthus altissima	17	2	X	-
Betula populifolia	7	3	X	-
Fraxinus pennsylvanica	3	19	-	X
Gleditsia triacanthos	0	2	-	X
Hamamelis virginiana	0	1	-	-
Juniperus virginiana	3	9	X	-
Liquidambar styraciflua	3	0	-	X
Malus spp.	3	4	X	-
Myrica pensylvanica	40	115	X	X
Nyssa sylvatica	16	1	X	X
Pinus echinata	9	1	X	Genus
Populus deltoides	1	0	-	"

(continued)

TABLE 1. (continued)

Species	Number Found On Landfill North Section	 South Section	Also Present In Woodlot	 Test Plot
Populus tremuloides	0	1	X	Genus
Prunus serotina	86	30	X	-
Quercus palustris	4	0	X	X
Rhus glabra	340	282	X	-
Robinia pseudoacacia	5	0	X	-
Rosa spp.	38	16	X	-
Sassafras albidium	3	3	X	-
Vaccinium corymbosa	18	19	X	-
Viburnum prunifolium	38	5	X	-

Total Area

Woodlot = 463,150 square feet = 10.63 acres
Landfill = 442,700 square feet = 10.16 acres
X = presence
- = not found
Genus = different species of same genus found

Site Conditions

The refuse in the Edgeboro landfill ranges in depth from 20 to 35 feet and consists primarily of municipal refuse plus some light industrial waste. The areas on the landfill where these data were collected were completed between 1966 and 1969. There is a foot or less of final soil cover over the refuse. No attempts have been made to vegetate this landfill; therefore, all vegetation observed growing on it consists of volunteer native species.

Ten permanent stations were established on the landfill where vegetation was either growing very well or not at all (Figures 3 and 4, Table 2). Acrylic gas sampling devices (Figure 5) designed to enable extraction of a micro-sample of the soil atmosphere for gas chromatographic analysis were buried at a depth of 10 inches at each of these stations.

The depth of cover material at the permanent stations was determined by digging five holes with a spade. Each approximately 18-inch diameter hole was dug until the refuse was reached. Then a yardstick resting on undisturbed soil was placed across the top of the hole. A second yardstick was used to measure the distance from the top of the cover. This distance was recorded as the depth of cover.

The soil atmosphere was analyzed by two methods, one utilizing a macrosample, one a microsample:

1) The macrosample was obtained by means of the MSA model 2A Explosimeter and Fyrite O_2 and CO_2 analyzers. The O_2, and CO_2, and combustible gas readings were all taken from separate holes within 1 foot of

each other when taken at the same station.

2) A microsample was obtained by first extracting a 5 ml. gas sample through the sampling device (Figure 5) with a syringe and discarding it. After extracting this volume, the tygon tubing was pinched to prevent a back flow of ambient air. A 0.5 ml. sample was then extracted through the sampling device with a gas-tight syringe and the sample sealed in the syringe by inserting the needle into a rubber stopper. The sample was then analyzed in a Carle model 8500 gas chromatograph equipped with a porpack Q and molecular sieve column system and a thermal conductivity detector.

The gas chromatograph was calibrated with standard gas concentrations supplied by Matheson Gas Products of East Rutherford, New Jersey. A flow of gas was established through a soft rubber tube, one end of which was attached to the regulator on the standard gas cylinder and the other end immersed in water to prevent a back flow of ambient air. A gas-tight syringe was then used to extract a 0.5 ml. sample through the tubing and inject it into the chromatograph. The recorder attached to the chromatograph was equipped with an intergration unit which translates the area under the gas peaks into standard units which were then plotted against the known concentrations of the gas to produce standard curves. The calibration procedure was performed once a month. Once a week a standard gas concentration was passed through the chromatograph to insure accuracy of the calibration curves.

TABLE 2. DESCRIPTION OF PERMANENT STATIONS ON THE COMPLETED SANITARY LANDFILL

Station	Description
A.	Oval area approximately 50 feet long by 38 feet wide. No vegetation growing in this area.
B.	Kidney shaped area about 500 feet long by 25 feet wide. Very little vegetation-only a few scattered clumps of brome grass covering less than 5% of the surface area.
C.	Circular area approximately 25 feet in diameter. At the center was a pin oak tree 15 feet high with a DBH of 8 cm. Moss was observed growing under the oak and brome grass grew all around it. The vegetation in this area provided 100% cover.
D.	Round clump of staghorn sumac about 15 feet in diameter. The sumac was about 6 feet high at the center. It appeared healthy, exhibiting good growth this season. Also in this area was a 10 foot high sweet gum tree with a DBH of 4.5 cm. It also exhibited good growth this season. The soil in this area tended to be very wet.
E.	Oval area approximately 20 feet long by 10 feet wide. Brome grass was growing in this area in sparse clumps providing about 25%

(continued)

TABLE 2. (continued)

Station	Description
	cover. This was the only poorly vegetated station where vegetation appeared to be increasing its percent coverage during the course of this study.
F.	Irregularly shaped 10 feet diameter group of staghorn sumac and peach trees. The sumac was 4.5 feet tall. It did not exhibit good growth this year. There were two peach trees, one about 4 feet high and one 6 feet high, which appeared healthy. The larger exhibited a good production of fruit in 1977.
G.	Round area about 25 feet in diameter. No vegetation was observed growing here.
H.	Round area about 25 feet in diameter. There was a good cover of brome grass and weeds in this area, providing close to 100% cover.
I.	Round area about 15 feet in diameter. A small group of peach trees about 6 feet high. These trees exhibited poor growth this year. There was also a 6-foot-tall crab apple tree with a DBH of 4 cm. that appeared healthy and grew well this year. There was a considerable amount of refuse on the surface in this area. Newspapers found in the refuse were dated January, 1969.
J.	Oval area approximately 18 feet long by 10 feet wide. The vegetation in this area provided less than 5% cover. It consisted of a few scattered clumps of brome grass and one chlorotic staghorn sumac 10 inches high. There was a considerable amount of refuse on the surface in this area. A newspaper found in the refuse was dated November, 1968.
K.	Irregular area approximately 15 feet in diameter. There was a healthy stand of peach trees here about 7 feet tall which grew very well in 1977.

Preparing The Experimental And Control Field Plots

Two field experiments were designed; one to screen tree species for adaptability to landfill conditions and the second to test gas-barrier systems for effectiveness in preventing contamination of root zones by landfill gases.

Species Screening Experiment--

One foot of sandy subsoil was spread over the entire experimental screening area followed by 8-10 inches of topsoil. Because there were two or three inches of original soil cover over the refuse prior to construction, this brought the total cover to approximately 2 feet.

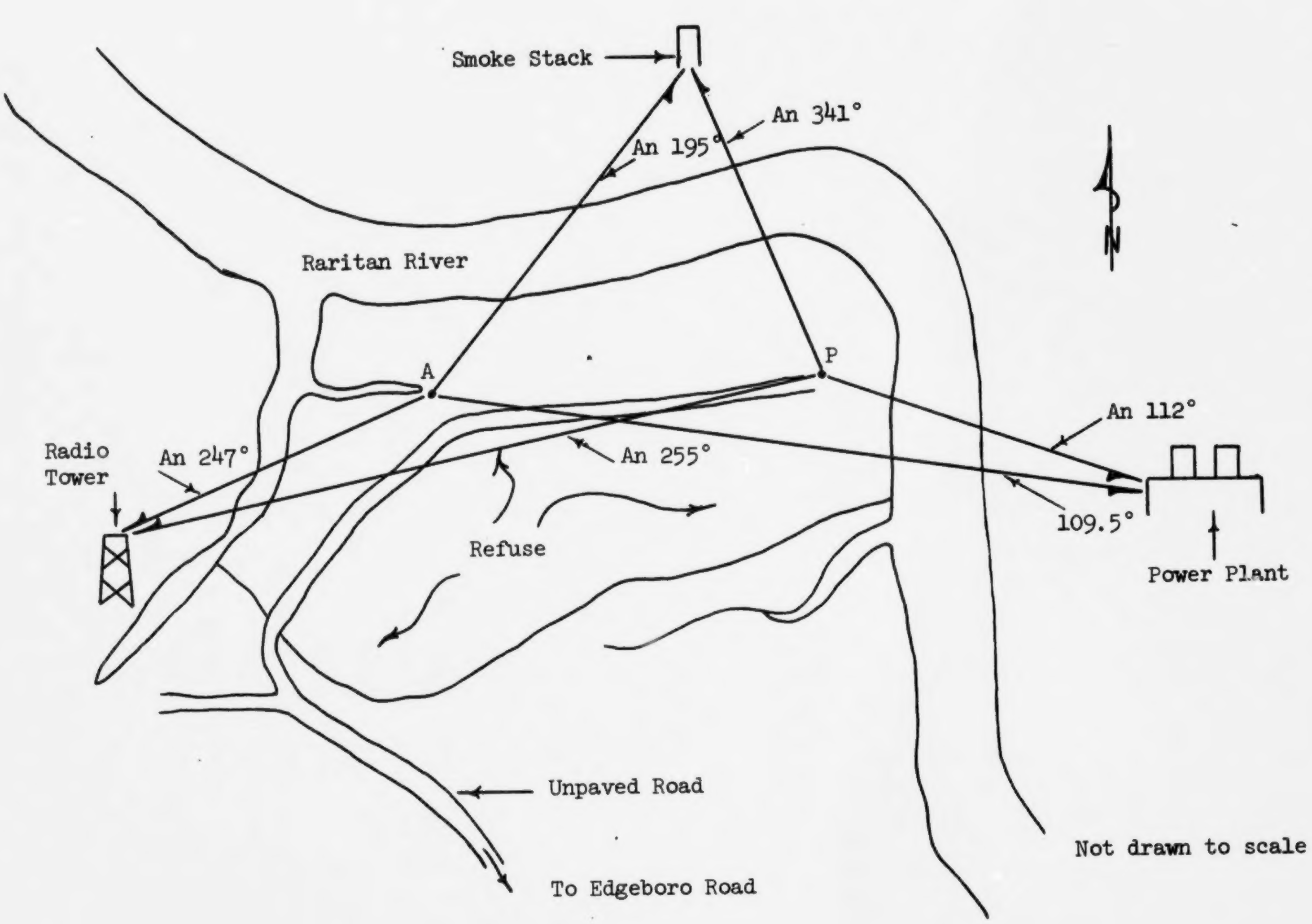
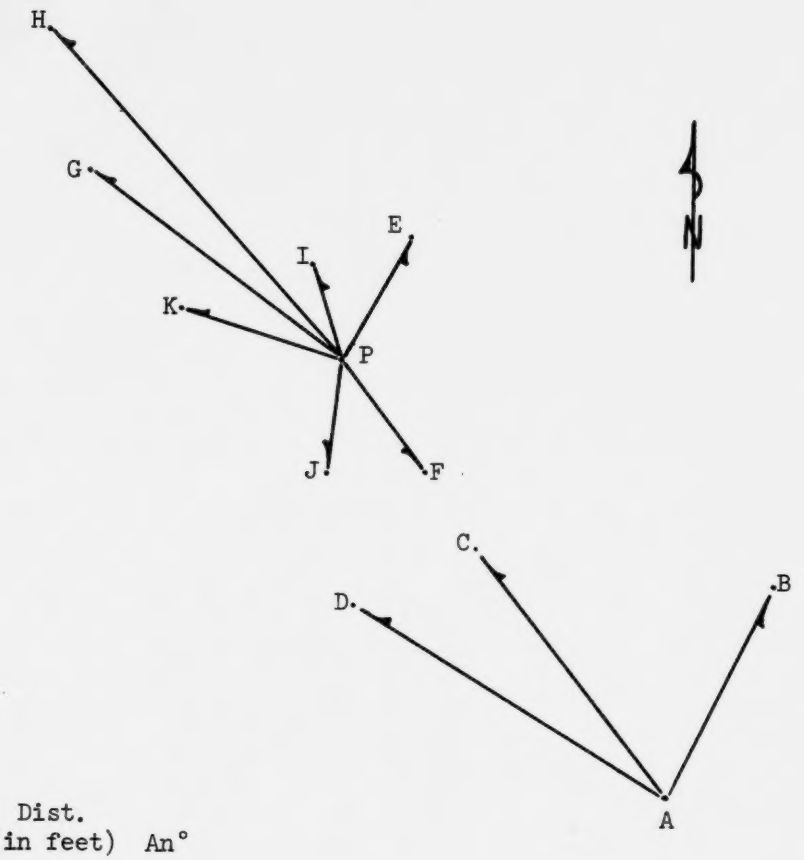
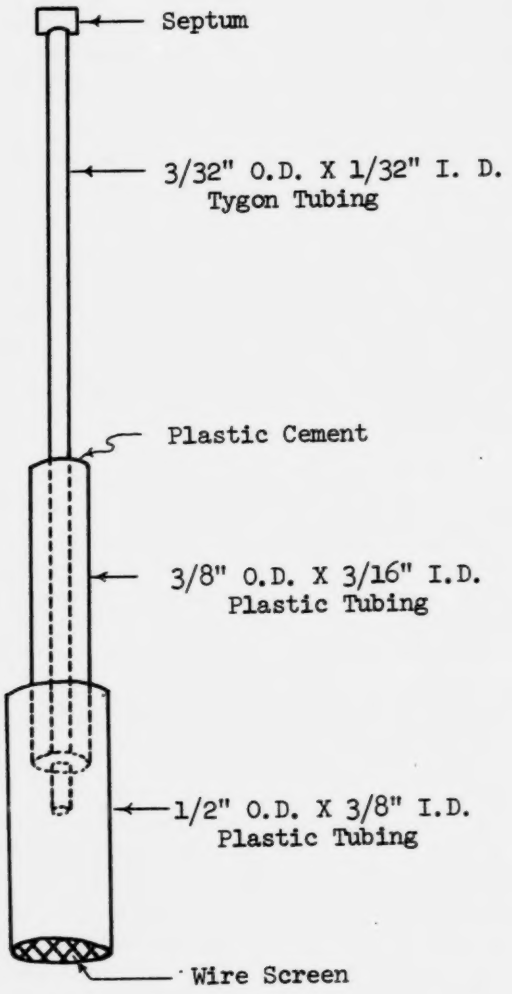

Smoke Stack
An 341°
An 195°
N
Raritan River
A
P
An 112°
Radio
Tower
An 247°
An 255°
109.5°
Refuse
Power Plant
Unpaved Road
Not drawn to scale
To Edgeboro Road

Figure 3. Edgeboro Sanitary Landfill, East Brunswick, New Jersey, location of reference stations for gas and vegetation sampling points.



From	To	Dist. (in feet)	An°
A	B	180	22
A	C	235	320
A	D	265	299
P	E	40	26
P	F	42	140
P	G	157	312
P	H	220	315
P	I	25	343
P	J	37	186
P	K	7	303

Figure 4. Gas and vegetation sampling points on Edgeboro Sanitary Landfill.



Septum
3/32" O.D. X 1/32" I. D.
Tygon Tubing
Plastic Cement
3/8" O.D. X 3/16" I.D.
Plastic Tubing
1/2" O.D. X 3/8" I.D.
Plastic Tubing
Wire Screen

Figure 5. Plastic soil gas sampler.

Following removal of the native vegetation, one foot of the same sandy subsoil spread on the experimental landfill plot was deposited on top of the control area. Eight to twelve inches of topsoil were then placed on top of the subsoil. The topsoil layer was about 2 inches deeper here than in the experimental plot. This was due to the need for extra soil to fill in the tracks created by the large tractor used to level the area.

Combustible gas readings were taken by means of the MSA Model 2A Explosimeter over much of the site at 50 foot intervals until a large enough area with high combustible gas concentrations was found.

The experimental plot measures 72'x108', an area large enough to accommodate ten replicates of nineteen different tree and shrub species and five landfill gas-barrier systems (Figure 6). The control is located approximately a quarter-mile from the experimental plot and is on a former undisturbed woodland. It measures 46'x110' and accommodates ten replicates of the same nineteen species planted on the experimental plot, in addition to two gas-barrier systems (Figure 7).

The experimental landfill plot is exposed to strong winds and driving rains, as is typical of many of the larger landfills. The control plot, located on the north side of an adjacent wooded rise, is only moderately exposed on the south and southwest where native woodlands remain. These native woods comprise sassafras, red oak, mockernut hickory, red maple and dogwood, species typical of a young forest community which normally follows 20-30 years after a disturbance such as a fire or clear cut.

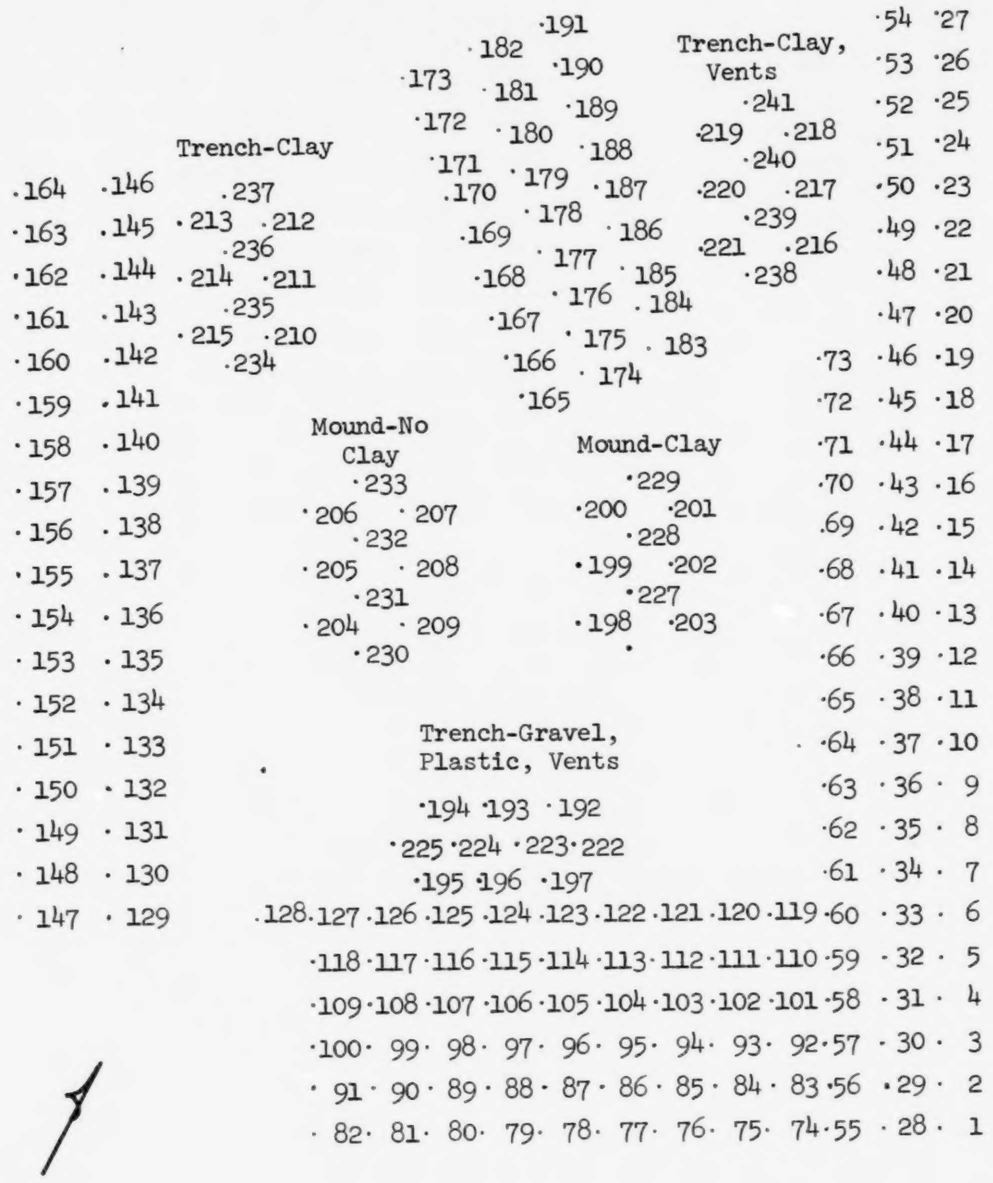
Drainage on both the experimental and control plots is good and should not be a limiting factor for tree growth.

Gas-Barrier Techniques--

Following the designation of the experimental plot, the precise boundaries for three 10'x14' trenches and two 14'x18' mounds were determined by selecting the areas of highest combustible gas concentration in the soil atmosphere. A caterpillar tractor bulldozer was used to dig the three 3 foot deep trenches and to move the excavated rubbish from the experimental site.

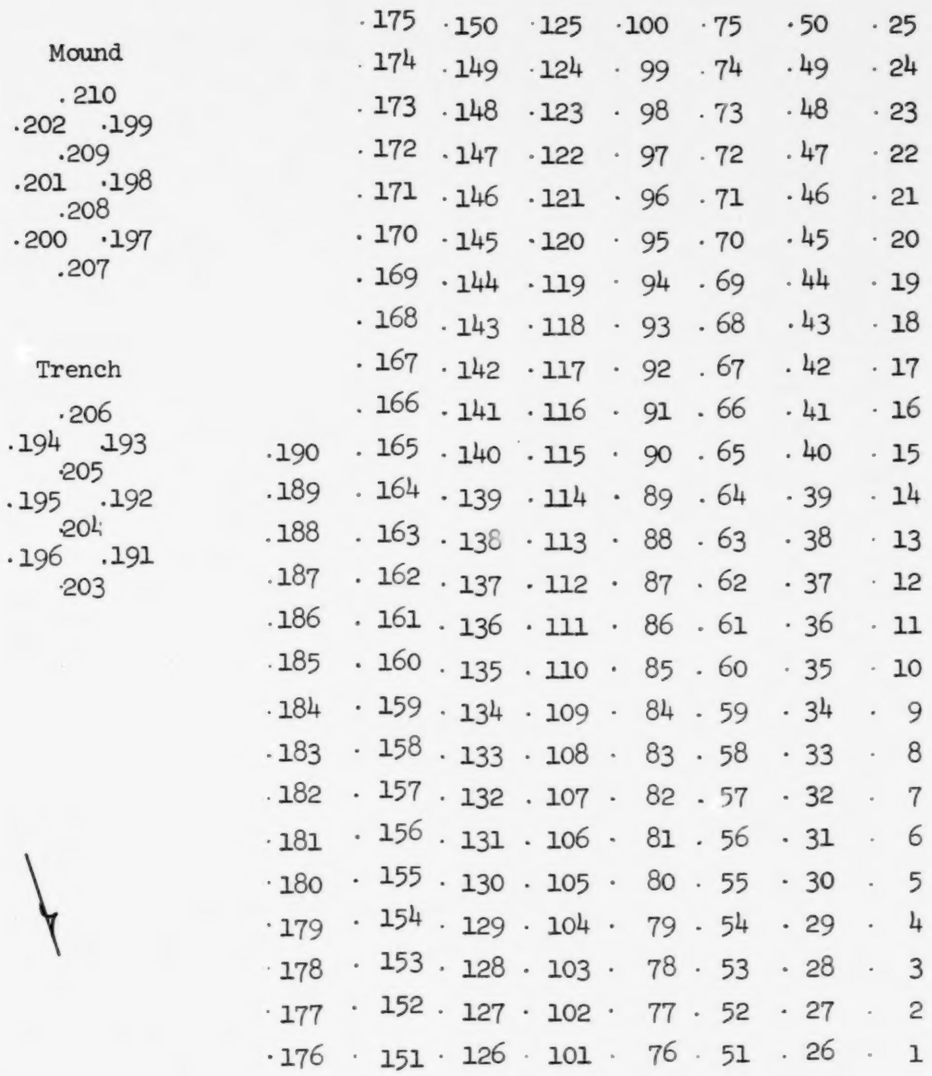
In order to prevent landfill decomposition gases from penetrating the soil, the three trenches were lined at the bottom with various barrier materials prior to backfilling with topsoil. One of the two mounds was underlain with a barrier whereas no barrier was used in the second mound.

Plastic/gravel/vents trench--This trench (Figure 8) was lined with a one-foot layer of 1 inch round road gravel which was deposited on the trench bottom by means of a front-end loader and spread out evenly with a hand rake. Two plastic gas samplers were buried in the gravel to permit the analysis of accumulated gas. Ten holes were then dug in the gravel around the periphery of the trench into which were placed ten 5-foot long, 4-inch diameter perforated polyvinyl chloride pipes. The perforations are ½ inch in diameter and are orientated at 90° angles at 6 inch intervals. A 16'x12' sheet of 4 mil polyethylene plastic was cut to fit over the PVC pipes and placed on


Trench-Clay
Trench-Clay, Vents
Mound-No Clay
Mound-Clay
Trench-Gravel, Plastic, Vents
164 163 162 161 160 159 158 157 156 155 154 153 152 151 150 149 148 147
146 145 144 143 142 141 140 139 138 137 136 135 134 133 132 131 130 129
237 213 212 236 214 211 235 215 210 234
173 172 171 170 169 168 167 166 165
182 181 180 179 178 177 176 175 174
191 190 189 188 187 186 185 184 183
241 219 218 240 220 217 239 221 216 238
233 206 207 232 205 208 231 204 209 230
229 200 201 228 199 202 227 198 203
194 193 192
225 224 223 222
195 196 197
128 127 126 125 124 123 122 121 120 119 60 33 6
118 117 116 115 114 113 112 111 110 59 32 5
109 108 107 106 105 104 103 102 101 58 31 4
100 99 98 97 96 95 94 93 92 57 30 3
91 90 89 88 87 86 85 84 83 56 29 2
82 81 80 79 78 77 76 75 74 55 28 1
73 72 71 70 69 68 67 66 65 64 63 62 61
54 53 52 51 50 49 48 47 46 45 44 43 42 41 40 39 38 37 36 35 34
27 26 25 24 23 22 21 20 19 18 17 16 15 14 13 12 11 10 9 8 7

Legend: Numbers identify specific trees
Trees spaced 4' apart

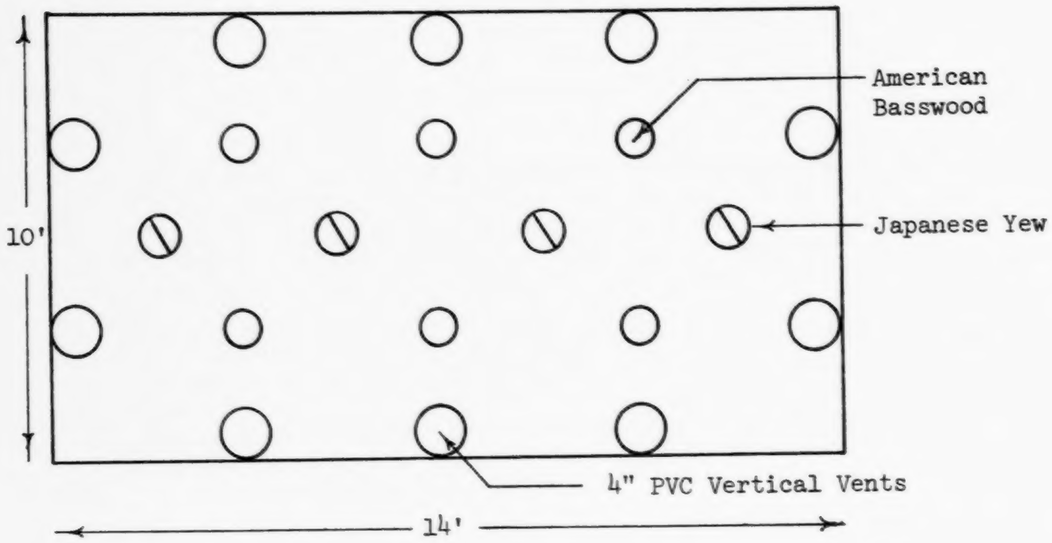
Figure 6. Location of trees on species screening area and gas-barrier techniques on experimental plot.


Mound
210
202 199
209
201 198
208
200 197
207
Trench
206
194 193
205
195 192
204
196 191
203
175 150 125 100 75 50 25
174 149 124 99 74 49 24
173 148 123 98 73 48 23
172 147 122 97 72 47 22
171 146 121 96 71 46 21
170 145 120 95 70 45 20
169 144 119 94 69 44 19
168 143 118 93 68 43 18
167 142 117 92 67 42 17
166 141 116 91 66 41 16
190 165 140 115 90 65 40 15
189 164 139 114 89 64 39 14
188 163 138 113 88 63 38 13
187 162 137 112 87 62 37 12
186 161 136 111 86 61 36 11
185 160 135 110 85 60 35 10
184 159 134 109 84 59 34 9
183 158 133 108 83 58 33 8
182 157 132 107 82 57 32 7
181 156 131 106 81 56 31 6
180 155 130 105 80 55 30 5
179 154 129 104 79 54 29 4
178 153 128 103 78 53 28 3
177 152 127 102 77 52 27 2
176 151 126 101 76 51 26 1

Legend: Numbers identify specific trees
Trees spaced 4' apart

Figure 7. Location of trees on species screening area and gas-barrier techniques on control plot.

Plan View


American Basswood
Japanese Yew
10'
4" PVC Vertical Vents
14'

End View

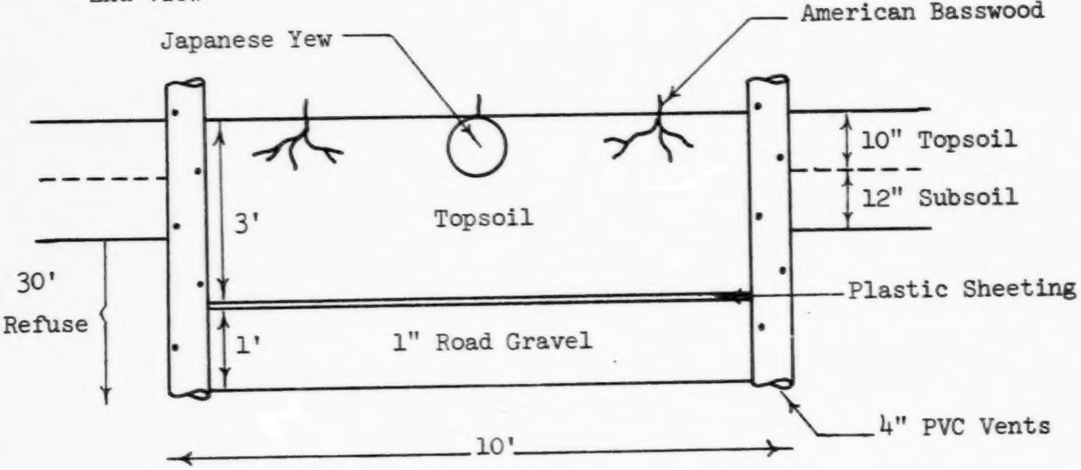

American Basswood
Japanese Yew
10" Topsoil
12" Subsoil
3'
Topsoil
30'
Refuse
Plastic Sheeting
1'
1" Road Gravel
4" PVC Vents
10'

Figure 8. Design of gravel/plastic/vents trench.

top of the road gravel. Presumably this made a seal through which no decomposition gas could migrate. It was expected that the gas collected under the plastic sheeting would be carried to the soil surface via the perforated pipes, thereby bypassing the 3-feet of topsoil backfilled into the trench. The tops of the ten perforated pipes extend approximately 1 foot above the soil surface.

Clay/vents trench--This trench (Figure 9) was lined at the bottom with a one-foot layer of clay similar to that used in California to exclude decomposition gases. The clay was obtained from virgin land about one-half mile away and brought to the site via a large earthscraper tractor. A front-end loader was then used to deposit the clay on the trench bottom. Some of the clay was friable and could be easily spread by hand shovel; however, a large portion of it had to be broken into smaller pieces to allow for better compaction. After the clay was adequately spread, it was packed down tightly by foot. Ten ventilation pipes, similar to those used in Figure 8, were placed vertically around the periphery of the clay bed, hopefully, to remove the gases of landfill decomposition prior to their entering the trench. Finally the trench was filled with 3-feet of topsoil.

Clay/no vents trench--This trench (Figure 10) was lined at the bottom with a foot-thick clay layer as was the previous trench. However, this trench has no perforated pipes for venting landfill gas. After the clay was spread and compacted, 3-feet of topsoil were backfilled into the trench.

Two experimental mounds were also constructed for preventing gas migration.

No clay mound--This mound (Figure 11) was constructed of the same quality topsoil as that used in the trenches. The final mound dimensions were 14'x18' at the base, 8'x12' at the top, and 3' in height with 45° sloping sides.

Clay barrier mound--To keep the landfill gases out of the root zone, this mound (Figure 12) (same dimensions as the previous mound) was underlain with a one-foot layer of the same type clay as used in trench-clay/vents and trench-clay. The clay base below the mound has an overall dimension of 16'x20' thereby extending one foot beyond the base of the mound.

The control plot contained one trench and one mound constructed to the same dimensions as those on the experimental plot with topsoil similar to that used on the experimental plot. No gas barriers or vents are associated with the trench or mound in the control plot.

Selection of Experimental Species

In order to test species representative of a maximum number of desirable landscaping characteristics and a variety of genotypes, plants were chosen from the following categories: deciduous shrubs, deciduous trees, needle-leaf evergreens and a broad-leaf evergreen. Within these categories, species were selected for: 1) tolerance to low oxygen tension environments; 2) tolerance to city conditions; 3) aesthetic landscaping purposes; 4) ubiquity; 5)

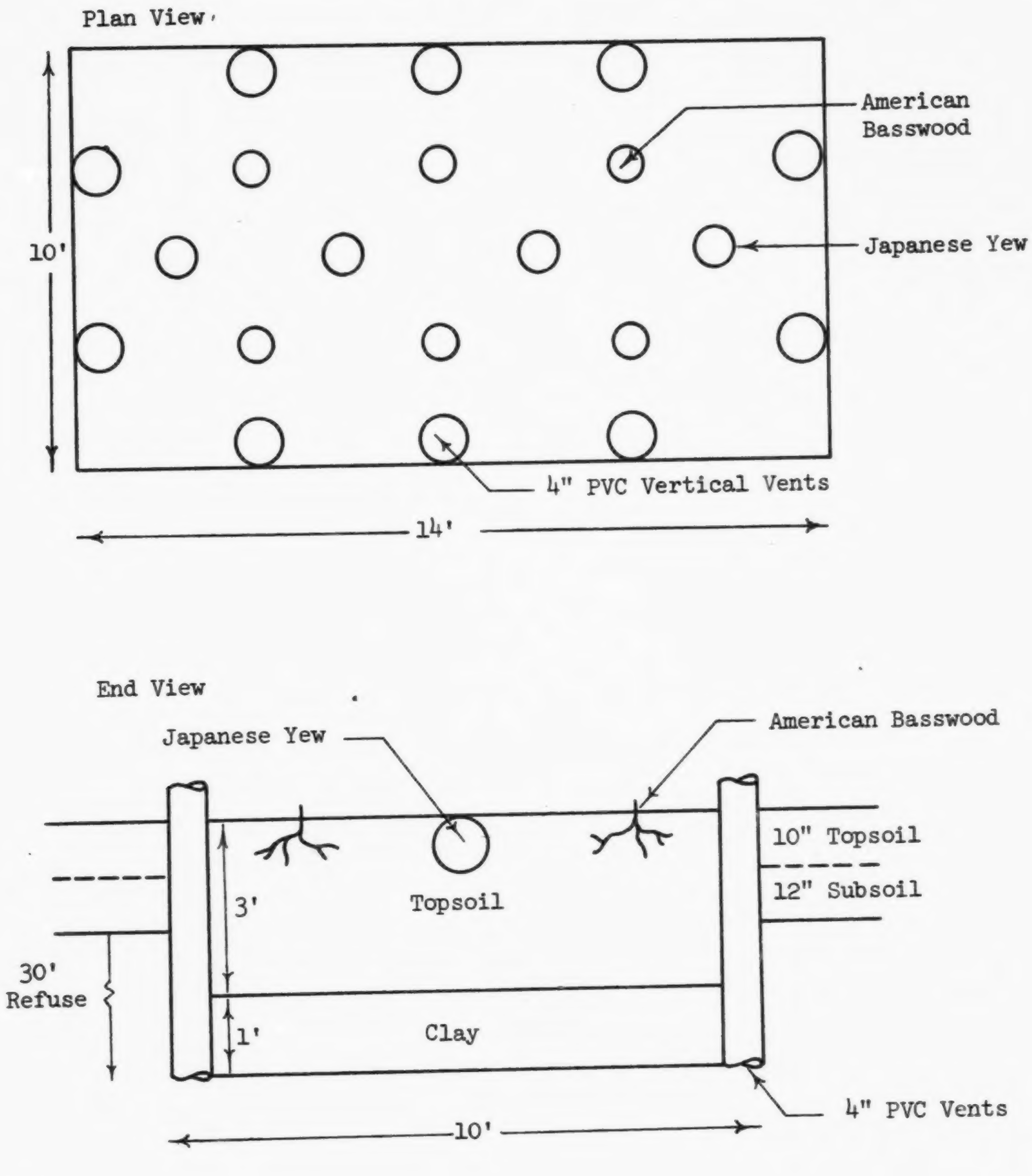
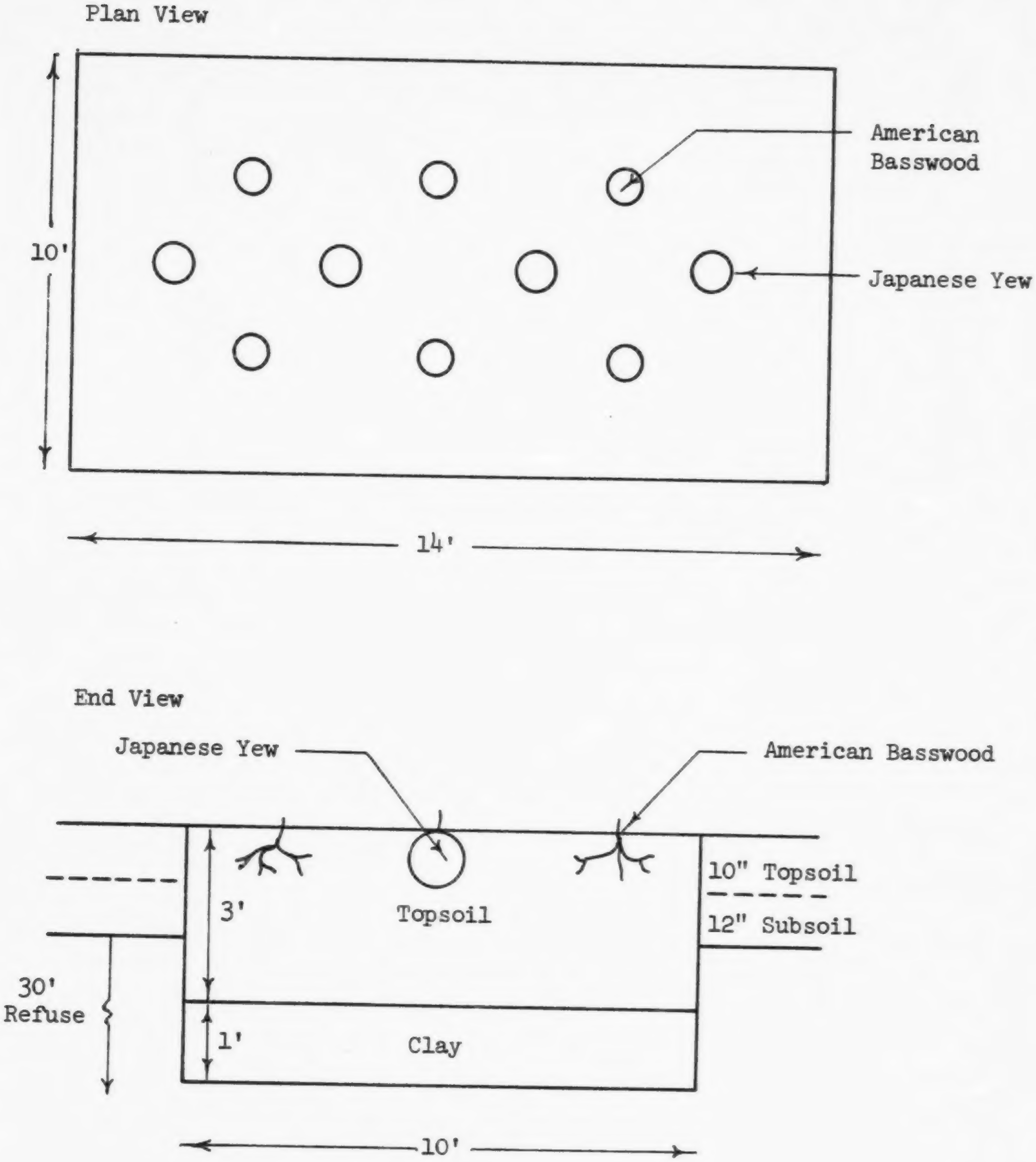

Plan View
American Basswood
10'
Japanese Yew
4" PVC Vertical Vents
14'
End View
Japanese Yew
American Basswood
10" Topsoil
12" Subsoil
3'
Topsoil
30' Refuse
1'
Clay
4" PVC Vents
10'

Figure 9. Design of clay/vents trench.



Plan View

End View

10'
American Basswood
Japanese Yew
14'
Japanese Yew
American Basswood
3'
Topsoil
10" Topsoil
12" Subsoil
30' Refuse
1'
Clay
10'

Figure 10. Design of clay/no vents trench.

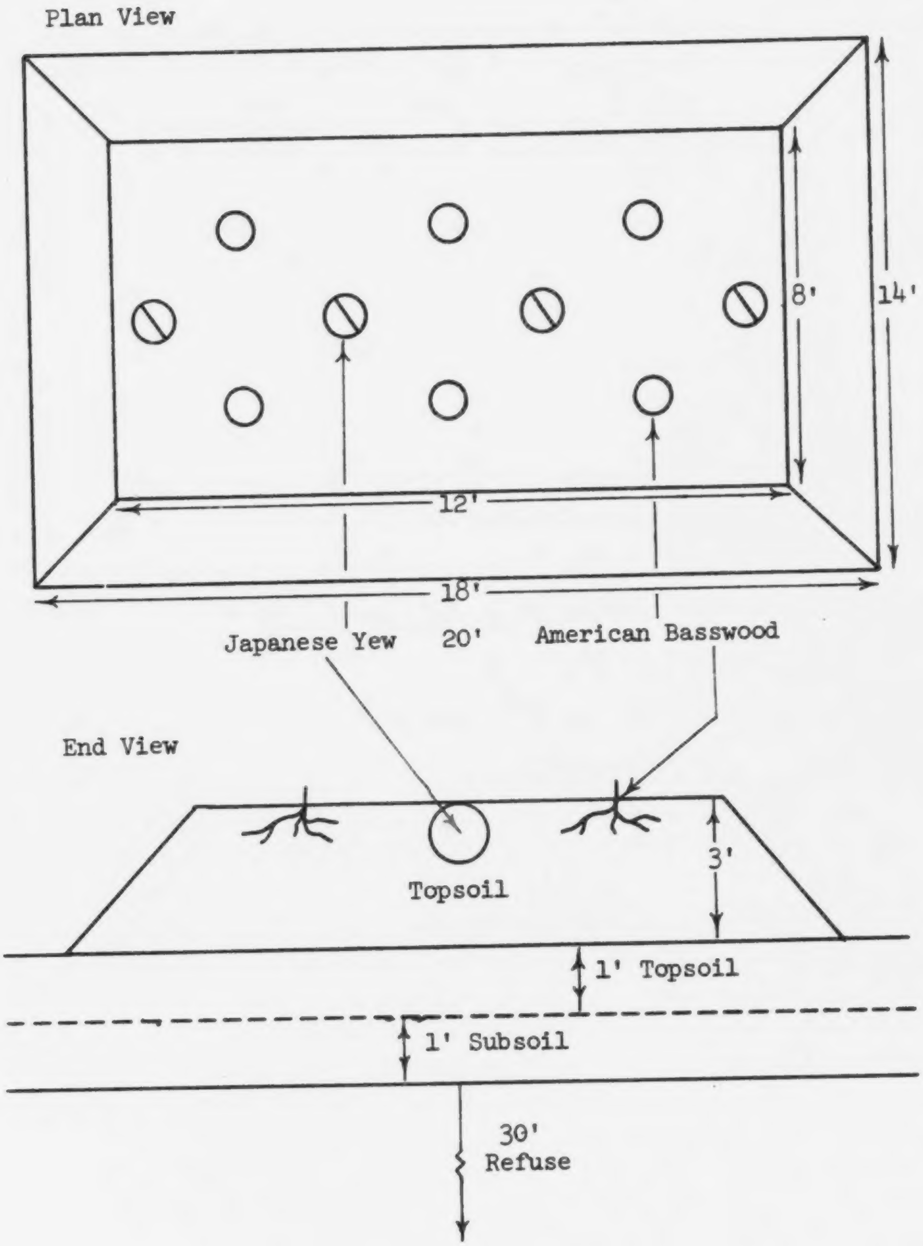

Plan View
8'
14'
12'
18'
Japanese Yew
20'
American Basswood
End View
Topsoil
3'
1' Topsoil
1' Subsoil
30'
Refuse

Figure 11. Design of no clay-barrier mound.

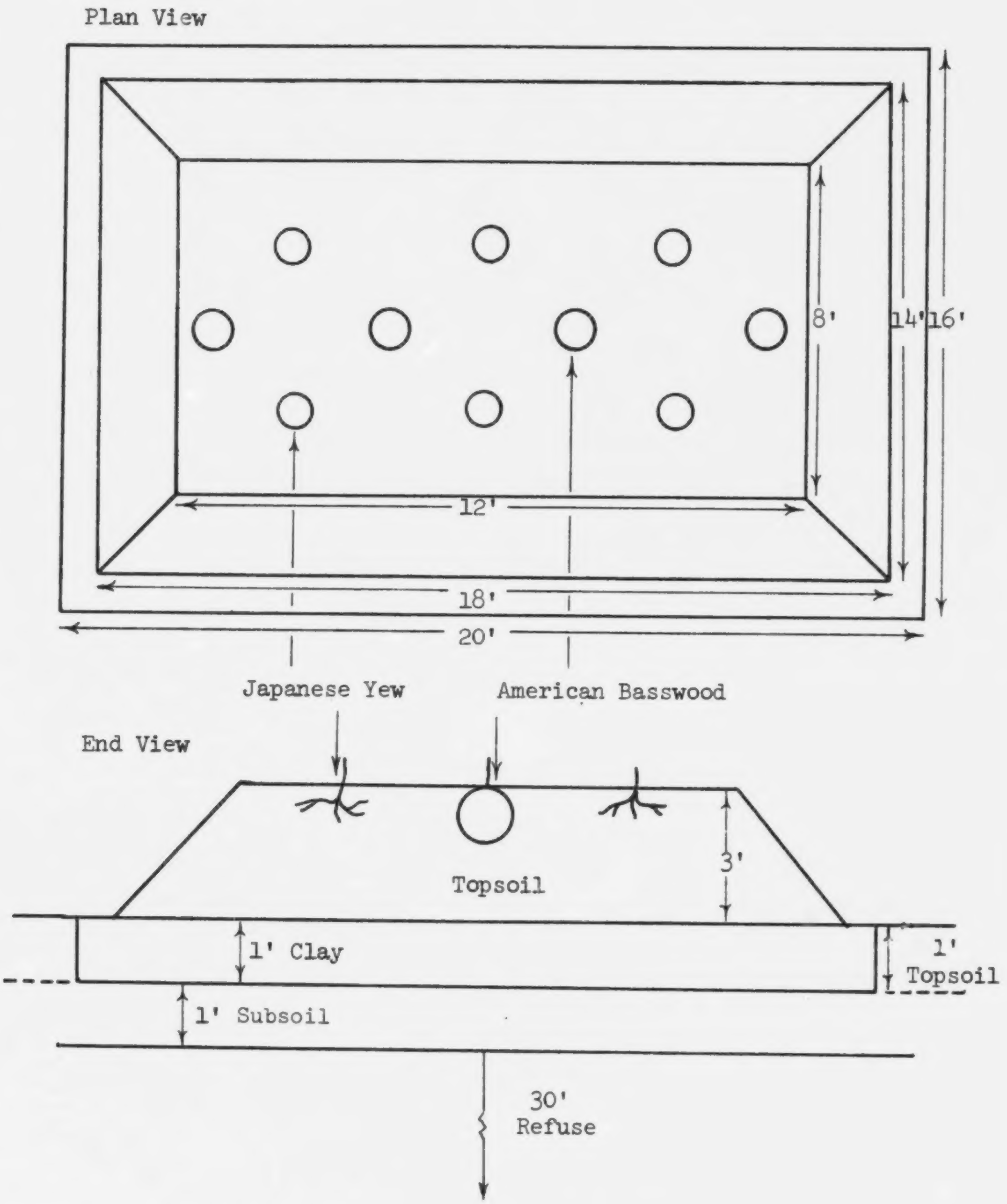

Plan View
12'
8'
14'
16'
18'
20'
Japanese Yew
American Basswood
End View
3'
Topsoil
1' Clay
1' Topsoil
1' Subsoil
30' Refuse

Figure 12. Design of clay-barrier mound.

susceptibility to natural and landfill gas injury; 6) tolerance to sea salt; 7) ease in transplanting; 8) minimal costs (Table 3).

Nineteen species (Table 4) were selected according to the above eight criteria. American basswood and Japanese yew were chosen for planting on the trenches and mounds because of their reported susceptibility to landfill gases. All species chosen for the experiment were judged to be relatively easily transplanted and obtainable at local commercial nurseries at a reasonable cost.

Planting of Trees and Shrubs

The trees were spaced at 4 foot intervals to allow for several years of growth uninhibited by adjacent trees. For random placement of the trees, points were marked in rows on the plot to accommodate all the trees. These points were assigned numbers in consecutive order on both plots from 1 to 210 and 1 to 240 (Tables 5a & 5b) (Figures 6 & 7) for the control plot and experimental plot respectively. For each species, ten of these numbers were selected from a random numbers table, and the ten replicates were planted in locations bearing these numbers on the dates shown in Table 6.

The planting holes were dug by means of a pick and shovel. Those for bare-rooted trees were dug deep enough to accommodate the vertical expanse of the root system and 3 to 6 inches wider than the lateral expanse. The balled and burlapped trees and the trees in containers were planted in holes as deep as the root ball or container and about 12 inches wider in diameter. The holes extended down into the sandy subsoil in the majority of cases.

As the trees were placed in the holes, the topsoil was backfilled to three-fourths of the original hole depth. The soil was packed firmly by foot and watered. When the water had been absorbed, the remainder of the hole was filled with topsoil and loosely packed by hand. A 2-inch ridge was constructed around each tree to act as a catch-basin.

Because of the loss of roots when the trees were dug at the nursery, the bare-rooted trees required branch pruning. This was done after the trees had been planted. Thirty to fifty percent of most of the viable branches was removed as well as all dead tissue.

The large deciduous trees were staked in order to stabilize them in the soil and prevent windthrow. Two 2"x2"x6' Douglas fir stakes were driven into the soil on either side of each tree perpendicular to the direction of the strongest prevailing winds. Plastic chain-lock was used to secure the tree between the two stakes.

Cultural Methods

Fertilizing--

In 1976, soil nutrient analyses for both the experimental and control plots indicated low nitrogen, phosphorus and potassium levels. In order to bring these nutrients to a medium level in the soil, on April 16-17, 1977, four pounds of 10:10:10 granular fertilizer were spread around each tree on

TABLE 3. TREE PLANTING SELECTION CRITERIA

	Trees	Tolerance to Low O_2 Tension Environments	Ubiquity	Aesthetic Landscaping Purposes	Sea Salt Tolerance	Tolerance to City Conditions	Susceptibility to Landfill Gases
DECIDUOUS TREES	Honey Locust			X			
	American Sycamore	X		X		X	
	Red Maple	X	X	X			
	Green Ash	X		X			
	Black Gum	X		X			
	Black Willow	X		X			
	Pin Oak	X		X			
	Ginkgo			X		X	
	Sweet Gum			X			
	American Basswood			X			X
	Hybrid Poplar			X			
	Mixed Hybrid Poplar			X			
DECIDUOUS SHRUBS	Euonymus			X			
	Bayberry	X		X			
BROADLEAF EVERGREEN SHRUB	Rhododendron			X			
NEEDLE LEAF EVERGREENS	White Pine			X			
	Japanese Black Pine			X	X		
	Norway Spruce			X			
	Japanese Yew			X			X

TABLE 4. SPECIES SELECTED FOR VEGETATION GROWTH EXPERIMENT AT EDGEBORO LANDFILL

Abbreviation	Latin Name	Common Name	Selection Criteria*
Ar	*Acer rubrum*	Red Maple	1,2,3
Ea	*Euonymus alatus*	Euonymus	3
Fl	*Fraxinus lanceolata*	Green Ash	1,3
G	*Ginkgo*	Ginkgo	3,5
Gt	*Gleditsia triacanthos*	Honey Locust	1,3
Ls	*Liquidambar styraciflua*	Sweet Gum	3
Mp	*Myrica pensylvanica*	Bayberry	1,3
Ns	*Nyssa sylvatica*	Black Gum	1,3
P	*Populus*	Poplar (Hybrid)	3
Pe	*Picea excelsa*	Norway Spruce	3
Pm	*Populus m*	Poplar (Mixed Hybrid)	3
Po	*Plantanus occidentalis*	American Sycamore	1,3,5
Ps	*Pinus strobus*	White Pine	3
Pt	*Pinus thunbergi*	Black Pine	3,4
Qp	*Quercus palustris*	Pin Oak	1,3
R	*Rhododendron Roseum elegans*	Rhododendron	3
Sb	*Salix babylonica*	Weeping Willow	1,3
Ta	*Tilia americana*	American Basswood	3,6
Tcc	*Taxus cuspidata capitata*	Japanese Yew	3,6

* Selection Criteria

1. Tolerant of low O_2 environments
2. Ubiquity
3. Aesthetic landscaping purposes
4. Sea salt tolerance
5. Tolerant to city conditions
6. Susceptibility to landfill gases

TABLE 5a. PLANT KEY FOR EDGEBORO LANDFILL TREE GROWING EXPERIMENT FOR THE CONTROL PLOT

Tree Number	Latin Abbreviation
1	Ea
2	Tcc
3	Fl
4	Ta
5	Fl
6	Ea
7	Po
8	Qp
9	Tcc
10	Po
11	Ar
12	P
13	G
14	Ps
15	Po
16	P
17	Ls
18	Tcc
19	Ta
20	Qp
21	Mp
22	Sb
23	Fl
24	Ls
25	Pe
26	Ns
27	Sb
28	G
29	Pt
30	R
31	Ps
32	G
33	Qp
34	Mp
35	Sb
36	Ea
37	Ar
38	Sb
39	Ls
40	Pm
41	Ar
42	Pm
43	P
44	Pe
45	P
46	Ps
47	Ns
48	Pm
49	R
50	Ph
51	Ta
52	Gt
53	Ls
54	Tcc
55	Sb
56	Mp
57	Pm
58	Ta
59	Po
60	Pt
61	G
62	Qp
63	Ns
64	Gt
65	Gt
66	Pm
67	Ps
68	Po
69	Pt
70	Ro
71	Po
72	Ar
73	Ls
74	Fl
75	R
76	Ns
77	Qp
78	Sb
79	Tcc
80	Pe
81	Qp
82	Pm
83	Tcc
84	Gt
85	Fl
86	Ta
87	R
88	Ps
89	Pe
90	Sb
91	Ns
92	Sb
93	Ps
94	Ea
95	Gt
96	R
97	Tcc
98	Ar
99	Ta
100	Pe
101	Ph
102	Ls
103	G
104	Ar
105	Ns
106	Pt
107	Ps
108	Sb
109	Pt
110	Pe
111	Pt
112	Pm
113	Mp
114	Po
115	Ea
116	R
117	Ar
118	G
119	Ls
120	Mp
121	Pm
122	Ar
123	Ls
124	Qp
125	Ea
126	Ea
127	Ps
128	Pt
129	Fl
130	Qp
131	Ps
132	Gt
133	Ta
134	Ea
135	Ph
136	Mp
137	Ns
138	Pe
139	Fl
140	G
141	Tcc
142	Po
143	Qp
144	Ph
145	R
146	Po
147	Ar
148	R
149	Po
150	G
151	Gt
152	Ph
153	Sb
154	R
155	G
156	Ea
157	Fl
158	Gt
159	Fl
160	Ar
161	Mp
162	Ns
163	Ph
164	Gt
165	Pe
166	Ea
167	Fl
168	Gt
169	Ta
170	Pm
171	G
172	Qp
173	Ls
174	Pm
175	Pt
176	Pe
177	Tcc
178	Ls
179	Ps
180	Pe
181	Ta
182	Mp
183	Mp
184	Pt
185	Ta
186	Mp
187	Pt
188	Ns
189	Ns
190	Tcc
191 - 202	Ta
203 - 210	Tcc

* See Table 4 for key to abbreviations

TABLE 5b. PLANT KEY FOR EDGEBORO LANDFILL TREE GROWING EXPERIMENT FOR EXPERIMENTAL PLOT

Tree Number	Latin Abbreviation
1	Pm
2	Tcc
3	Po
4	Ta
5	Po
6	Ea
7	Fl
8	Qp
9	Ea
10	Fl
11	Ar
12	P
13	G
14	Ps
15	Fl
16	Fl
17	Ls
18	P
19	Ta
20	Qp
21	Mp
22	Tcc
23	Po
24	Ls
25	Pe
26	Ns
27	Ta
28	Sb
29	G
30	Pt
31	R
32	Ps
33	G
34	Qp
35	Mp
36	Tcc
37	Pe
38	Ns
39	Ls
40	Sb
41	Pm
42	Ea
43	Pm
44	P
45	Pe
46	P
47	Ps
48	Ns
49	R
50	Ta
51	P
52	Ta
53	Gt
54	Mp
55	Ls
56	Ar
57	Ps
58	Mp
59	Pm
60	Ta
61	Fl
62	Pt
63	G
64	Qp
65	Ar
66	Gt
67	Gt
68	Pm
69	Ar
70	Tcc
71	R
72	Fl
73	Pt
74	Ls
75	Tcc
76	R
77	Ns
78	Qp
79	Ta
80	Sb
81	Pe
82	Qp
83	Pm
84	Po
85	Gt
86	Po
87	Ta
88	R
89	Mp
90	Pe
91	Sb
92	Ar
93	Pt
94	Ps
95	Sb
96	Mp
97	R
98	Ps
99	Ar
100	Ea
101	Pe
102	P
103	Ls
104	G
105	Ar
106	Ns
107	Pt
108	R
109	Sb
110	Ea
111	Pe
112	Mp
113	Pm
114	Qp
115	Fl
116	Ns
117	Ps
118	Ar
119	Ls
120	G
121	Gt
122	Ea
123	Pt
124	Ls
125	Tcc
126	Ea
127	Sb
128	Ps
129	Pt
130	Po
131	Qp
132	Ps
133	Gt
134	Ta
135	Tcc
136	P
137	Mp
138	Ns
139	Pe
140	Fl
141	G
142	Pm
143	Po
144	Qp
145	Ea
146	Mp
147	P
148	R
149	Fl
150	Ar
151	R
152	Fl
153	G
154	Gt
155	P
156	Sb
157	G
158	Sb
159	Tcc
160	Po
161	Gt
162	Ea
163	Po
164	Pt
165	Ar
166	Pt
167	Ns
168	Po
169	Gt
170	P
171	Tcc
172	Ns
173	Ea
174	Pe
175	Gt
176	Ta
177	Pm
178	G
179	Qp
180	Ls
181	Pt
182	Mp
183	Pm
184	Pt
185	Tcc
186	R
187	Sb
188	Ps
189	Pe
190	Ls
191	Ns
192 - 221	Ta
222 - 241	Tcc

* See Table 4 for key to abbreviations

TABLE 6. TREE AND SHRUB PLANTING DATA

	Dates of Planting		
Screening Experiment	Site A (Control Plot)	Site B (Experimental) Plot	Approximate Tree Height at Planting
Honey locust (a)*	4-22-76	4-4-76	7'-8'
American sycamore (a)	4-27-76	4-6-76	10'-12'
Red maple (a)	4-22-76	4-4-76	6'-8'
Green ash (a)	4-22-76	4-6-76	10'-12'
Black gum (c)	4-15-76	4-9-76	3'-4' (8" cans)
Weeping willow (a)	4-27-76	4-15-76	14'-15'
Norway spruce (b)	4-14-76	4-8-76	18"-24"
White pine (b)	4-15-76	4-8-76	18"-24"
Euonymus (b)	4-27-76	4-27-76	15"-18"
Bayberry (b)	4-10-76	4-9-76	12"-15"
Pin oak (a)	4-27-76	4-4-76	6'-8'
Rhododendron (c)	4-15-76	4-6-76	12"-18" (6" cans)
Ginkgo (a)	4-22-76	4-4-76	5'-6'
Japanese black pine (b)	4-10-76	4-8-76	18"-24"
Japanese yew (b)	4-27-76	4-8-76	18"-24"
Sweet gum (c)	4-26-76	4-26-76	3'-4' (8" cans)
American basswood (a)	4-22-76	4-23-76	7'-8'
Hybrid poplar (a)	4-6-76	4-3-76	9'-10'
Mixed hybrid poplar (a)	4-15-76	4-3-76	1'
Barrier System Experiment			
Basswood - trenches	4-23-76	4-23-76	7'-8'
Basswood - mounds	4-23-76	4-23-76	7'-8'
Yew - trenches	6-10-76	6-10-76	18"-24"
Yew - mounds	6-10-76	6-10-76	18"-24"

* Shipping Method:

(a) Bare-rooted
(b) Balled and burlapped
(c) Containerized

both plots for a total of 840 pounds with a standard granular fertilizer-spreader.

Liming--

Both plots were limed with pulverized dolomitic-limestone on April 18, 1977. In order to raise the pH to 6.5, forty-six lbs./1000 square feet were applied to the control plot and fifty-seven lbs./1000 square feet to the experimental plot by means of a standard walk-behind spreader.

Irrigation--

The rainfall in New Brunswick in the early spring of 1976 and 1977 was enough to maintain the soil at a moisture level sufficient for adequate tree growth, but by the middle of May in both years, the soil moisture* had reached a low enough level to warrant irrigation. During the summer of 1976, a one-horsepower irrigation pump with a 3/4 inch outlet hose was used to allocate water to each tree. The water was pumped from a series of four 55-gallon drums located in the back of a pick-up truck. Approximately three gallons were applied to each tree at each irrigation period at a rate of 200 gal./hour. This method of irrigation was quite time-consuming and provided only a limited amount of water for each tree.

On July 10, 1977 an alternative method of irrigation was made available. A 2000-gallon fuel-oil truck was converted into a water-supply truck by the Herbert Sand and Gravel Company and arrangements were made to utilize this truck for irrigating the trees. Approximately ten gallons were now applied to each tree at each watering at a rate of 2000 gal./hour. When the weekly rainfall was inadequate, the plots were irrigated on the weekend by this more efficient method which allocated more water/tree in a shorter period of time.

Pest Control--

On July 7, 1976, the following tree species were sprayed with liquid Sevin: pin oak, American sycamore, green ash, red maple, ginkgo, American basswood, hybrid poplar, and mixed hybrid poplar for the control of gypsy moth, tent caterpillars and canker worms which were already present on some of the experimental trees and on many of the surrounding trees growing naturally on the landfill. A second spray was applied on July 18, 1976 for the same insect species.

On May 6, 1977, the following tree species were sprayed with liquid Sevin for the control of tent caterpillars and canker worms which were present on some trees: particularly the pin oaks, American basswoods, weeping willow and hybrid poplar.

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*Soil moisture was tested by the squeeze method, i.e. when a handful of soil was squeezed and water dripped from the soil, it was classified as wet; when no water came out but the soil stayed together in a clump the soil was moist; and when the soil crumbled after squeezing, the soil was considered dry and the plants were irrigated.

Rodent Control--

On December 29, 1977, a $\frac{1}{2}$ inch mesh screen supported by three stakes was placed around each euonymus shrub to prevent damage by rabbits.

Plot Maintenance--

During the growing season, grass and weeds were periodically cut with a power mower and weeds were pulled from the area immediately surrounding each tree trunk. Tree support-stakes were driven back into the ground when loosened and the plastic chain-lock supporting trees between stakes was replaced when necessary.

Sampling Methods

Soil Gas Analyses--

During the summer of 1976, combustible gas was measured in situ by means of a Mine Safety Appliance Model 2A Explosimeter. A $\frac{1}{2}$ inch hole was punched in the soil to the desired depth by means of a commercial bar-hole maker. The sample was withdrawn from the bar-hole by use of a 3-foot long nonsparking probe. A rubber stopper was placed over the upper end of the sampling probe to help seal the bar-hole from the ambient air. The Wheatstone bridge principle is used within the instrument for determining the concentration of combustible gases.

Gas data were taken at a 1-foot soil depth from eleven collection points on the experimental plot and eight points on the control plot on 7/7/76 and 9/13/76. Gas data were also collected from the trenches and mounds of the gas-barrier technique experiments on these same dates. Measurements were made at the 1-foot soil depth at six points within each gas-barrier technique and at four or six points around the periphery of the trenches, as well as within the vent pipes.

During 1977, gas samples were collected from forty-eight buried samplers approximately every two weeks, beginning in March and ending in August, when all plants had ceased growing. Forty-two of the sampling stations were on the experimental plot (Figure 13) and six on the control plot (Figure 14). The device in Figure 5 was used for obtaining the soil gas samples. In the experimental screening area, one sampler is in place for each group of six plants, whereas in the trenches and mounds, there is a sample for each group of five plants.

Soil Temperature Analyses--

Soil temperatures at the 1-foot depth were collected at the same sample points (Figure 13 & 14) and on the same dates as the gas samples.

Soil Moisture Analyses--

Beginning in mid-March, 1977, soil moisture measurements were made on six samples from the experimental screening area and four from the control (Figures 13 & 14). One measurement was made in each of the gas-barrier techniques. Samples were collected at approximately two-week intervals at times when the moisture content was considered to be the lowest, i.e. before irrigation or before a rain was expected. A sample was obtained using a 3-inch diameter soil auger in the following manner: two 8-inch deep holes

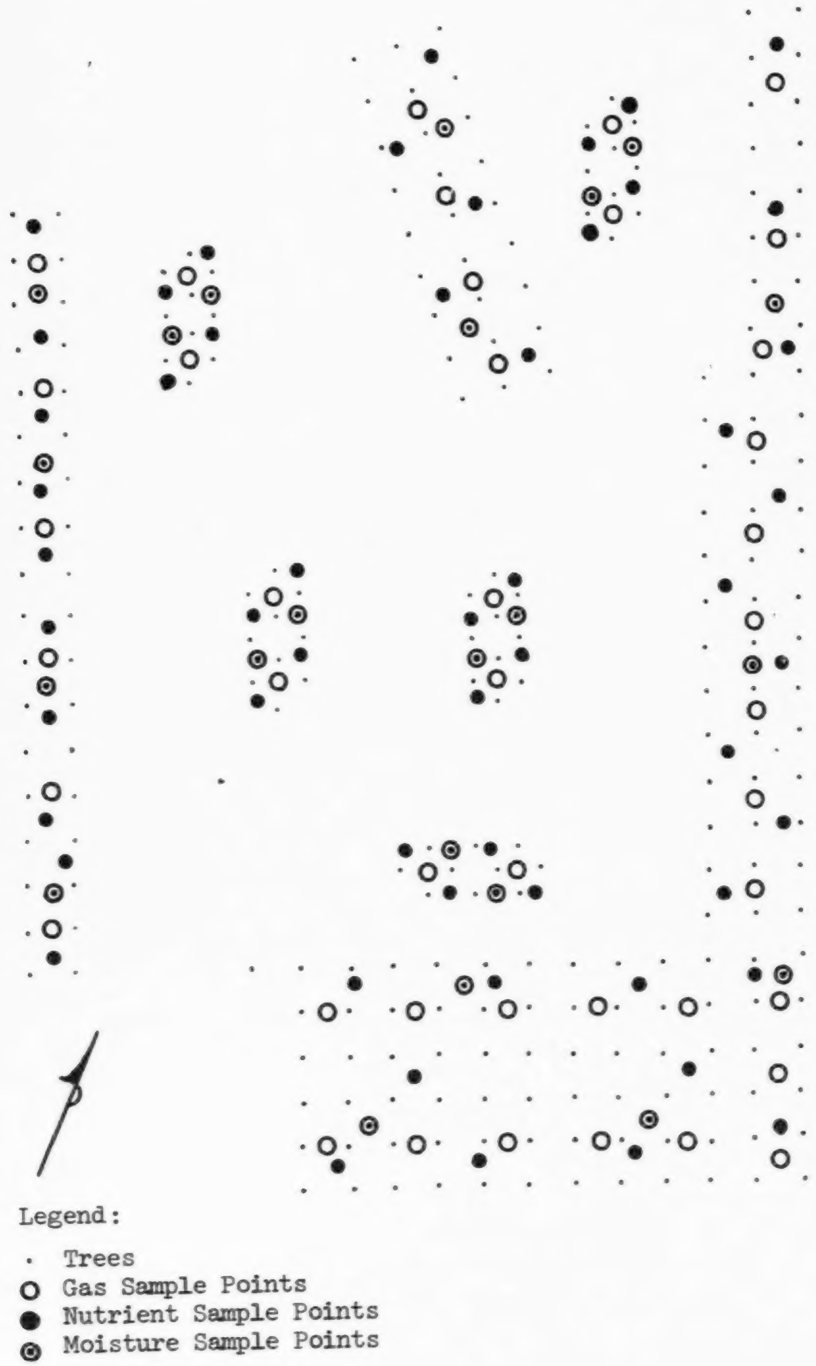

Legend:
· Trees
○ Gas Sample Points
● Nutrient Sample Points
◎ Moisture Sample Points

Figure 13. Location of soil variable sampling stations on experimental landfill plot.

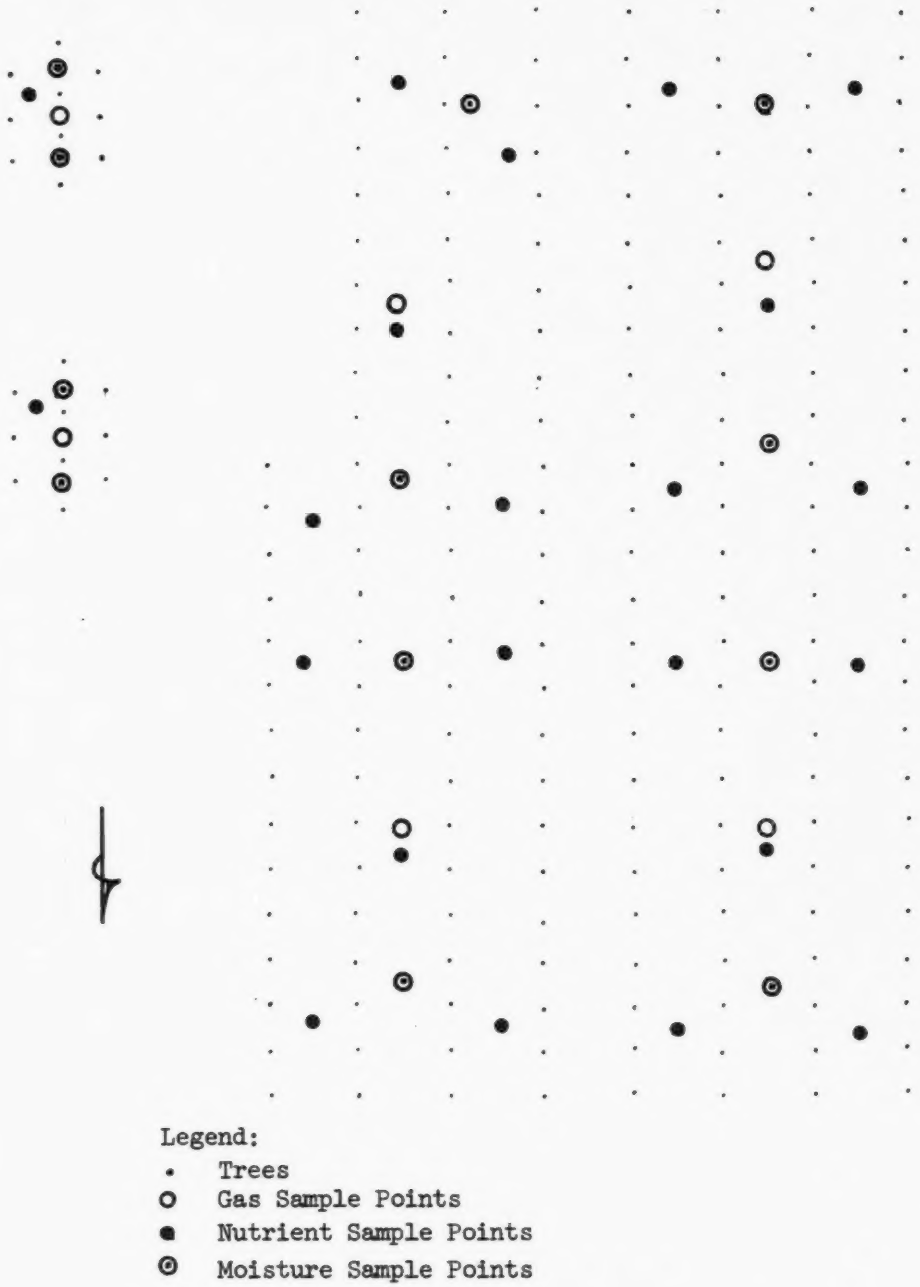

Legend:
• Trees
○ Gas Sample Points
● Nutrient Sample Points
⊙ Moisture Sample Points

Figure 14. Location of soil variable sampling stations on control plot.

were dug in the same general area and the soil from these two holes was placed into a bucket and mixed with a spade. A 400 ml. metal container was then filled with this soil mixture and capped to retain all the moisture.

After all the samples were collected, each was sieved through a 2 mm. sieve and weighed together with the container and lid and placed in a drying oven @ 100-110°C, then reweighed after twenty-four hours of drying. The soil was then removed from the container and the container and lid were weighed together. This tare weight was then subtracted from both the wet weight of soil plus container weight, and dry weight of soil plus container weight, to give actual wet and dry soil weights. Moisture content percentage was then calculated from these adjusted soil weights to give percent moisture on a dry weight basis.

Soil Nutrient Element Analysis--

On October 15, 1976, June 15, 1977 and October 20, 1977, seven soil samples were collected from the experimental screening area and four from the control screening area for chemical analyses. Each sample consisted of combined soils from five 8-inch-deep holes within each representative area (Figure 13 & 14). For each barrier technique the soil from four 8-inch-deep holes was mixed together and the sample was taken from this mixture.

Soil Bulk Density Analysis--

Soils were measured for bulk density in each barrier technique and in both the experimental and control screening area in the summer of 1977.

Measurements were made in the following manner: a 3-inch diameter - 3-inch long metal core (Figure 15) was placed inside a soil auger. A hammer made to fit over the top of the auger was fitted into place and the auger was driven into the soil until it was 3 inches into the ground. The auger was then pulled from the ground, the core with soil inside removed from the auger and placed into a cardboard container. The samples were dried for approximately twenty-four hours @ 90-100°C until all moisture was removed from the soil particles. The soil was then weighed and the data recorded as g/cc.

On the experimental screening area two measurements were taken at each of six locations (i.e. @ the same locations where moisture content samples were collected) (Figure 13). On the control screening area two measurements were taken at each of four locations totaling twenty measurements for both plots (Figure 14). In each of the seven planting techniques, four measurements were taken, for a total of twenty-eight measurements.

Tree Root Biomass--

A measurement of root biomass was obtained for each plant on both plots between June 13 and June 25, 1977. A 3-inch diameter soil auger was used to bore a 12-inch deep hole, 1.5 feet from the base of each tree in the northerly direction. All the material from this hole was placed into a bucket. The roots were then picked from the soil in the bucket and placed in a small envelope. At the end of each day's root collection, the envelopes were placed in a drying oven for approximately twenty-four hours. The soil clinging to the roots was shaken free and the roots were then weighed.

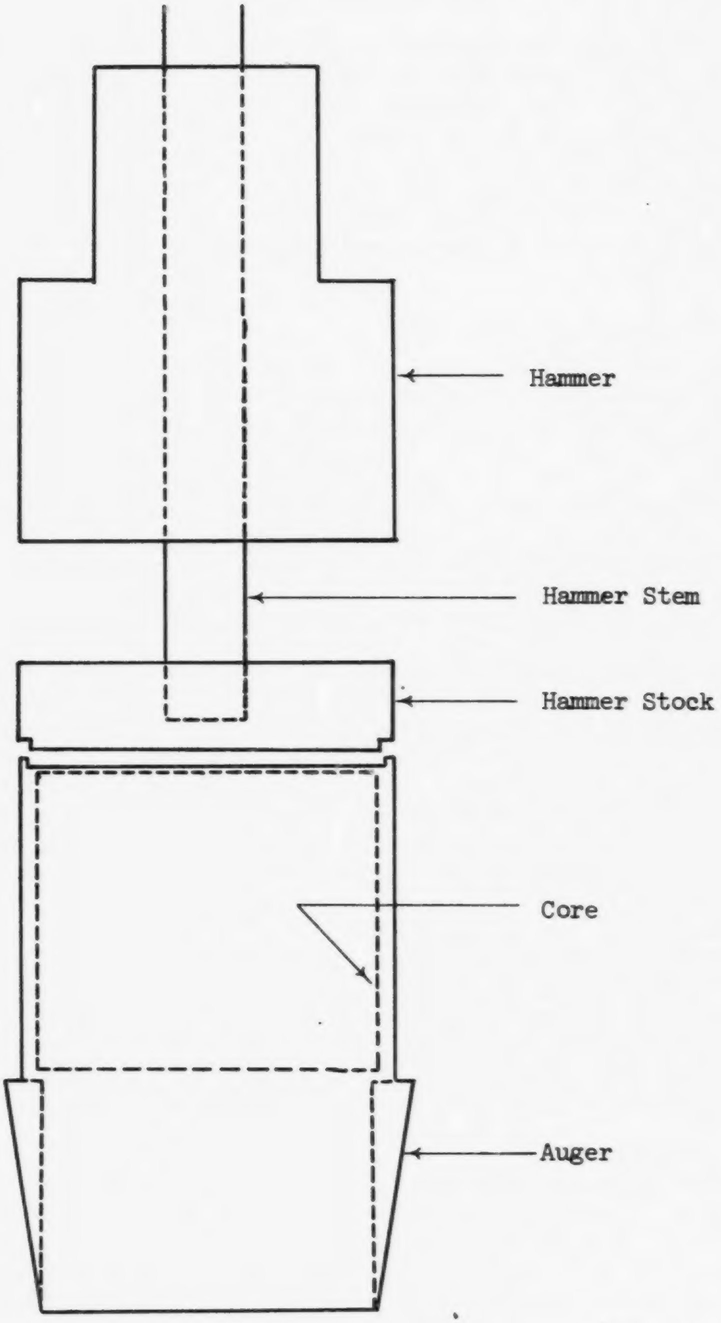

Hammer
Hammer Stem
Hammer Stock
Core
Auger

Figure 15. Hammer and auger used for collecting soil bulk density sample.

Tree Shoot Length--

In 1976, shoot length measurements (in cm.) were used as indicators of the vigor and growth response of each tree to its immediate soil environment. Four measurements were taken per tree - the length of the leader shoot which would become the main trunk and the lengths of the three next longest shoots.

The nature of shrub growth is different from that of the trees in that no true leader shoot is produced. Therefore, the four longest shoots were measured on these plants instead of a leader and three longest shoots measured on the trees.

In order to measure the shoot length in 1977 for a particular plant, six shoots were selected from each deciduous tree, shrub and Japanese yew in the following manner: when the plants stopped growing, six shoots were randomly selected on each plant. Each shoot was measured from the past year's bud scale scar to the tip of the current year's terminal bud. This was repeated for all deciduous plants and yew except mixed hybrid poplar.

Because evergreen trees and mixed hybrid poplar produce a true leader shoot, it was measured in addition to five other shoots selected at random from each plant.

Tree Stem Basal Area Increment--

On March 14-16, and on September 17-18, 1977, stem diameter (in cm.) was measured on every plant in both plots with metal tree calipers. The following nine species were measured at a point 30 cm. from ground level: red maple, green ash, American sycamore, hybrid poplar, weeping willow, American basswood, ginkgo, honey locust and pin oak. The remaining ten species were measured somewhat lower on the trunk at distances from the ground indicated in Table 7. A small spot of white paint was placed at the point on the trunk where the measurement was taken. This permitted other measurements to be taken at the end of September from the same point. The stem diameters were converted to cross-sectional stem basal area. The data are reported as percent increase in cross-sectional basal area from March to September.

Tree Leaf Weight--

In order to measure the amount of leaf biomass produced by each plant, four leaf weight samples were collected from each plant in 1977. The procedure for deciduous trees and shrubs and Japanese yew follows:

1. Select four shoots at random from a plant, i.e. one from each compass direction (N,S,E&W).

2. From each of these four shoots, collect all the leaves (needles) from last year's bud scar to this year's terminal bud and place those from each shoot in a separate bag. Dry for approximately twenty-four hours at 150°F and then weigh.

For evergreens, excluding Japanese yew:

1. Collect all the needles along the current year's leader shoot and

place them in a bag.

2. Select three other shoots, two from the top whorl and one from the whorl second from the top. Collect needles from these three shoots and place them in three separate bags.

The needles were oven-dried for approximately twenty-four hours at 150°F and then weighed.

TABLE 7. DISTANCE FROM THE SOIL SURFACE AT WHICH STEM INCREMENT WAS MEASURED

Species Latin Name	Common Name	Distance from Soil (cm)
Acer rubrum	Red Maple	30
Euonymus alatus	Euonymus	5
Fraxinus lanceolata	Green Ash	30
Ginkgo biloba	Ginkgo	30
Gleditsia triacanthos	Honey Locust	30
Liquidambar styraciflua	Sweet Gum	8
Myrica pensylvanica	Bayberry	3
Nyssa sylvatica	Black Gum	8
Poplus	Hybrid Poplar	30
Poplus	Mixed Hybrid Poplar	5
Picea glauca	Norway Spruce	3
Platanus occidentalis	American Sycamore	30
Pinus strobus	White Pine	5
Pinus thunbergi	Japanese Black Pine	5
Quercus palustris	Pin Oak	30
Rhododendron elegans	Rhododendron	3
Salix babylonica	Weeping Willow	30
Tilia americana	American Basswood	30
Taxus cuspidata capitata	Japanese Yew	3

Physical Condition of Trees--
At monthly intervals during the summer of 1977, observations were recorded for every tree which showed signs of stress. Leaf loss, scorch, chlorosis, dieback and wilt were included as signs of stress. At the end of the growing year, each tree was given a number from 0 to 5 based on the physical appearance of the tree. Zero indicated a dead tree and five the healthiest.

Statistical Methods

Analysis of variance, Student's "t" and multiple stepwise regression techniques were employed for data analysis (135). Library programs of the Bio-Med (BMD) series and Statistical Analysis System (SAS) at the Rutgers University Computer Center were employed.

In the analysis of variance, the response variables were leaf weight, shoot length, root biomass and basal stem area increment. Data for these variables were collected on each of the ten replicates for each species on the experimental and control plots, as well as on all ten trees planted in each gas-barrier technique.

In the regression analysis, American basswood was chosen for study because it was growing in those areas (i.e on the gas-barrier techniques) which exhibited a wide range for the soil variables included in the analysis. Ten independent variables were considered: soil gases (six variables) - oxygen, lowest oxygen, carbon dioxide, highest carbon dioxide, methane, highest methane; soil temperature (two variables) - temperature and highest temperature; soil moisture content (one variable) and soil bulk density (one variable). The limits imposed on the regression were: significant F values, R^2 and all coefficients with $P < 0.05$. A prediction equation was then calculated for each response variable (i.e. leaf weight, shoot length, root biomass, basal stem area).

Environmental Conditions

Weed Growth--

Weeds including goldenrod, ragweed, mustard plant and a variety of grasses established themselves over much of the area on both the experimental and control plots. However, the control plot was covered more quickly and more completely than the experimental plot. The grasses comprised a greater portion of the weeds on the control plot.

The two mounds on the experimental plot and the mound and the trench on the control area supported weed growth similar to the gravel/plastic/vents trench which exhibited the best vegetative growth in general.

Hurricane Effects--

On August 10, 1976, Hurricane Belle passed within 50 miles of East Brunswick, New Jersey, site of the landfill experiment depositing 2.4 inches of rain and reaching wind velocities of 46 miles per hour from the northwest. In spite of the chain lock securing each tree to stakes, the wind caused damage to trees on both the experimental and control plots.

Twenty-one trees on the control plot were shifted substantially in the soil by the strong winds. Seven of these were blown over to the extent that their trunks formed a 45° angle with the ground. The trees most affected were the tallest i.e. green ash (#7 & 61) weeping willow (80, 91, 127) and American sycamore (84 & 86). These seven trees were placed in the erect position and restaked. Tree #154, a rhododendron, was split in half at the base of the stem and had to be removed from the site.

On the experimental plot, three green ash trees (10, 15, 16) were blown about so that a much enlarged hole was created around the base of the trunk. The soil was quite loose in the root zone because some large roots had been moved in the soil. These trees had to be restaked and the soil packed down around the roots to ensure that the small roots again had contact with the soil. One of the green ashes (#10) had broken loose from the chain lock securing it to the stakes, allowing the trunk to rub against one of the stakes and causing the bark and part of the cambium to be scraped off for 14 inches along the trunk. Also affected was a Japanese black pine (#181) which was blown over to about a 45° angle with the soil. This tree was placed in an erect position and the soil packed down to ensure good root contact with the soil.

Drainage--

The overall slope of the sites was measured with an Abney hand level. The slope in the north-south direction on the experimental plot was slightly greater (2°) than on the control (1°) which gave the experimental plot better drainage than the control. The east-west slopes were about 1° on both plots.

The difference in drainage between the two plots was very noticeable following Hurricane Belle in August 1977. Ponding of water was observed on the control plot for five days following the hurricane whereas ponding on the experimental plot lasted only one day.

SIMULATED LANDFILL STUDIES

Selection of Gas Concentrations for Greenhouse Studies

In order to select realistic concentrations of landfill gas components for inclusion in simulated mixtures for greenhouse studies, soil gas concentrations of twenty sanitary landfills visited throughout the continental United States were measured between August 1975 and January 1977 (52). Of these landfills five had completed filling since 1966 or were still operating when the data were collected. Only landfills which contained municipal refuse which was not burnt were used in this study. Seven of the sanitary landfills had a reported average refuse depth of more than twenty feet and twelve had an average depth of less than twenty feet of refuse. Information concerning the landfills was obtained by questioning landfill operators and public works employees.

Sampling sites were chosen by visually examining the landfill for types of vegetative growth and sampling was done on areas indicative of the types of vegetation observed. The samples were obtained by making a hole to a depth of one foot with a $\frac{1}{2}$ inch diameter bar-hole maker. Once the hole was made the bar-hole maker was quickly removed and a hollow steel probe was inserted into the hole which was then sealed with a rubber stopper. A MSA Model 2A Explosimeter was then used to extract a sample through the probe. This instrument provides a reading of the percent combustible gas in the sample.

The MSA Explosimeter is sensitive to all combustible gases. The sample is drawn over a heated catalytic filament which forms part of a balanced Wheatstone bridge electrical circuit. The combustion raises the temperature of the filament, thereby increasing resistance in proportion to the concentration of combustibles in the sample. This unbalances the electrical circuit causing a deflection of the current meter pointer which indicates on the scale the concentration of combustible gas in the sample. This instrument was calibrated by means of a MSA (Part #454380) calibration kit supplied by the manufacturer. Frequent calibration is necessary since the filament may become contaminated with use.

The approximate concentrations of oxygen and carbon dioxide were obtained by using Bacharach Fyrite Model CPD O_2 and Model CUD CO_2 analyzers. The Fyrite gas analyzers operate on the Orsat principle of gas analysis. A sample of the gas to be analyzed is contained in a space of known volume from which the O_2 or CO_2 is removed from the gas mixture by selective absorption into fluids in the analyzer. The removal of the O_2 or CO_2 from the sample decreases the pressure exerted by the gas sample on the fluid. The fluid is in contact with the atmospheric pressure by means of an elastic diaphragm so that as the gas is absorbed the fluid replaces the gas mixture being measured. The intrusion of the fluid into the space originally occupied by the sample provides a measurement of the amount of O_2 or CO_2 removed.

The quality of the fluid in the CO_2 analyzer is determined by exhaling a deep breath into the instrument and if it fails to record 2 to 4% CO_2 in the sample the fluid is replaced. The fluid in the O_2 analyzer is checked by sampling the ambient air and if it fails to read 20 or 21% O_2 in the sample the fluid is replaced.

The Effect of Simulated Landfill Gas on Two Maple Species

To investigate the ability of tree seedlings to survive in soil atmospheres contaminated with excessive amounts of carbon dioxide (CO_2) and methane (CH_4), two species of maple were chosen: red maple (*Acer rubrum*) because of its ability and sugar maple (*Acer saccharum*) because of its inability to withstand flooding. These species were compared in order to determine if the species more tolerant to flooding was also more tolerant to soil atmospheric contamination with CO_2 and CH_4.

Cultural Methods--

One-year old red and sugar maple seedlings were purchased bare-rooted from Hess Nursery of Cedarville, New Jersey. The seedlings were planted (5 each) in 12 20-gallon modified galvanized steel trash cans (Figure 16) containing a soil mix of 1 part peat and 2 parts loam, on May 1, 1977. The soil was sterilized by heating to 180°F in an electrical sterilizer for 24 hours.

Fumigation Methods--

The seedlings were divided into three treatments with 20 seedlings (10 of each species) in each treatment (Figure 17). For treatment 1 the soil in each can was fumigated with a gas mixture containing approximately 3% O_2, 40% CO_2, 50% CH_4 and 7% N_2. Treatment 2 was a control with compressed ambient air forced through the soil. The compressed air and the gas mixtures were supplied by Matheson Gas Products Inc. of East Rutherford, New Jersey. In treatment 3 the seedlings were flooded by filling the cans with water to a depth of several inches above the soil line. In order to fumigate the soil, two cans were attached in series to a cylinder containing the gas mixture and equipped with a two-stage gas regulator. Prior to planting the seedlings it was determined that a gas flow of 120 to 250 ml. per minute was necessary for each pair of cans in order to adequately saturate the soil.

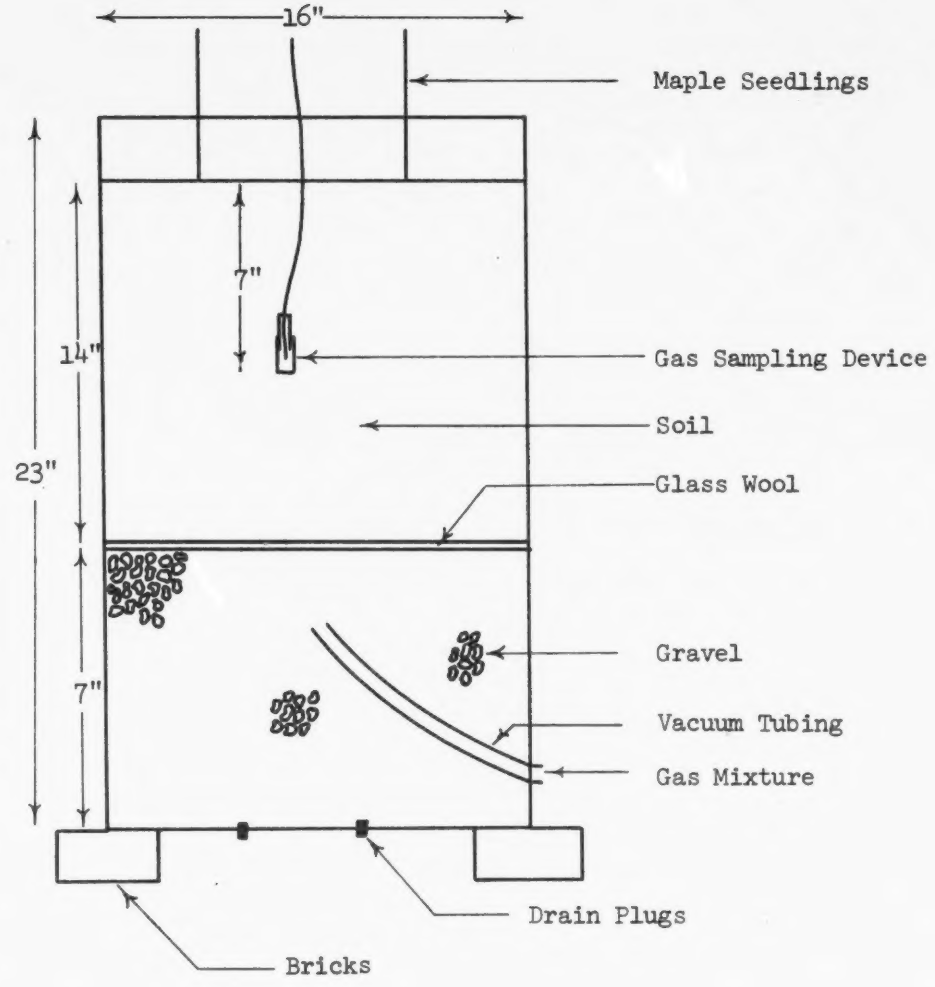

16"
Maple Seedlings
7"
14"
23"
Gas Sampling Device
Soil
Glass Wool
Gravel
7"
Vacuum Tubing
Gas Mixture
Drain Plugs
Bricks

Figure 16. Modified galvanized steel trash can used to fumigate maple seedlings.

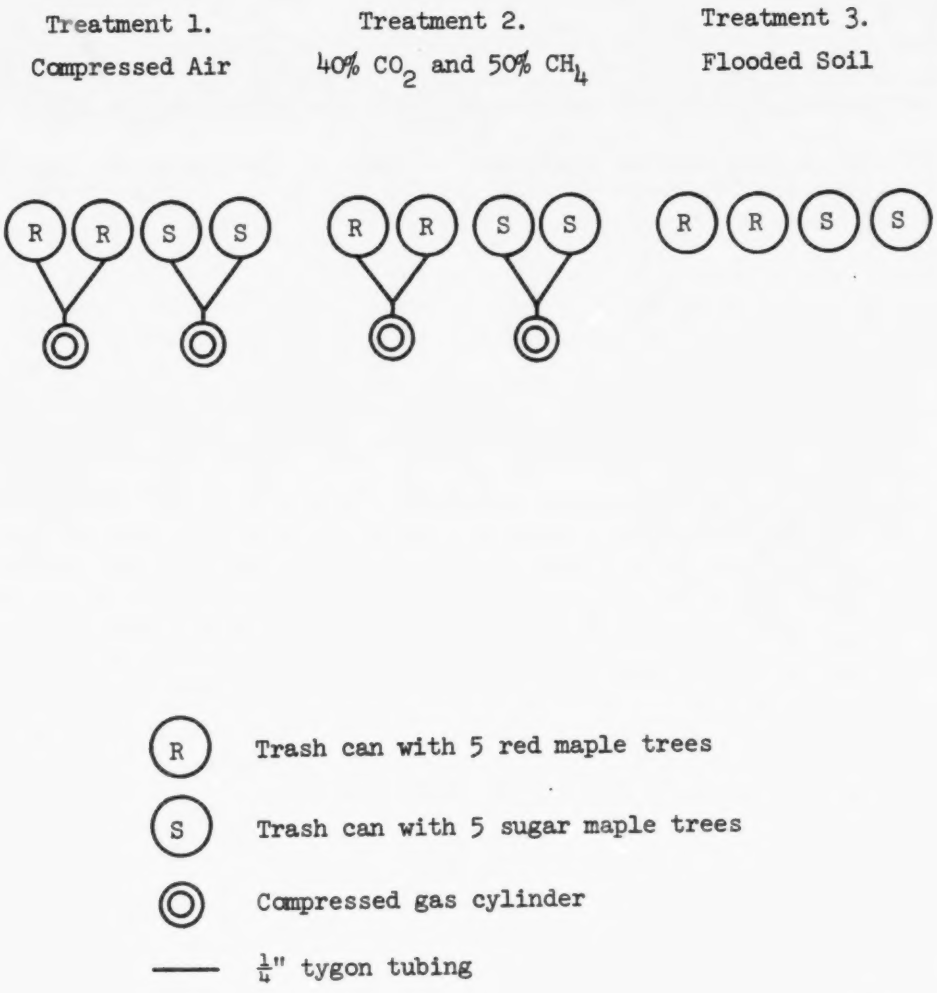

Treatment 1.
Compressed Air
Treatment 2.
40% CO_2 and 50% CH_4
Treatment 3.
Flooded Soil
R
R
S
S
R
R
S
S
R
R
S
S
R
Trash can with 5 red maple trees
S
Trash can with 5 sugar maple trees
Compressed gas cylinder
¼" tygon tubing

Figure 17. Design of red and sugar maple fumigation experiment.

The gas flow was established by disconnecting the tubing from the cylinder to the two trash cans and establishing the desired flow in air with a soap bubble flowmeter. This done, the tubing was reconnected. The flow of gas through the soil was not determined.

The composition of the soil atmospheres was monitored by extracting a 0.5 ml. sample of air from devices (Figure 5) buried at a 7 inch depth in the soil and analyzing it with a Carle model 8500 gas chromatograph (134).

The fumigations did not begin until August 9, 1977 by which time the seedlings had completed most of their seasonal growth. They were from 2-to 4-feet tall at this time.

Analytical Methods--

Transpiration measurements--The physiological condition of the seedlings was monitored by periodically measuring the rate of transpiration with a Lambda Instruments Diffusive Resistance Porometer. This instrument measures water vapor that evaporates off of the leaf surface and consists of a sensor which is a modified hygrometer whose electrical resistance varies inversely with humidity and a portable resistance meter. The instrument was calibrated by means of an acrylic plate with holes drilled in it which was placed over filter paper saturated with water to simulate the stomatal resistance. If the root system was damaged, the tree would be unable to take up water fast enough to support normal transpiration. Readings were taken only on leaves which were fully illuminated and in the upper one-third of the seedling. Measurements of transpiration rate were obtained only on sunny days. It required two to three hours to take transpiration measurements on all sixty seedlings. Therefore, sampling had to be performed in such a way as to compensate for the changes in illumination caused by movement of the sun or the occurrence of clouds. This was done by taking readings on only two seedlings in each can before moving on to the next one. After all the cans had been sampled in this manner, measurements were begun again on the remaining three seedlings in each can. If the weather changed after the sets of two readings were completed but before the rest of the data were collected then only the data obtained in the first sets were reported. If the weather conditions changed noticeably before the first sets of two readings were completed, the data were not reported.

Soil gas analyses--The composition of the soil atmosphere in treatments 1 and 2 was monitored regularly during the course of the experiment. From August 9 through August 25, the flow of gas as it came out of the cylinder was 120 ml. per minute for each group of two trash cans. From August 26 through August 29 treatments 1 and 2 were discontinued due to an interruption of the gas delivery. From August 30, for the duration of the experiment, the flow of gas coming out of the cylinder was 220 ml. per minute for the two cans containing the sugar maples and 250 ml. per minute for the two cans containing the red maples. The increased flow of gas to the red maples was found to be necessary in order to maintain a soil atmosphere similar to that given the sugar maples. On September, 20, 21 and 22, the gas treatment was discontinued to the red maples receiving CO_2 and CH_4 due to problems with the regulator. The control seedlings were fumigated with compressed air at the same rate of flow used for the corresponding species in treatment 1.

This experiment was terminated on September 27, 1977.

Statistical methods--Where there were two means to be compared the data were statistically analyzed by means of Student's "t" test. Where more than two means were involved statistical significance was determined by means of analysis of variance (135).

The Effect of Simulated Landfill Gas on Tomato Plants in Solution Culture

Cultural Methods--

Rutgers tomato plants were grown in specialized 4-liter culture vessels in sand solution culture (Figure 18). The plants were watered daily with a solution containing nutrients in the following molar concentrations; .0019 M K_2SO_4, .0016 M KH_2PO_4, .0045 M $Ca(NO_3)_2$, .001 M $MgSO_4$, .0004 M $(NH_4)_2SO_4$, .0005 M H_3BO_4, .0005 M $FeSO_4$, .00044 M EDTA and a trace element mix.

When the plants were about 1 foot high, the lower leaves were pruned and lids were placed on the glass vessels (Figures 18 & 19). Cotton impregnated with heavy duty silicon vacuum grease and vaseline was used to provide a seal around the stems of the plants. Tygon tubing was attached to the vessel outlets for drainage and to the gas inlets and outlets for gas flow. Flower and lateral shoot buds were pruned in order to concentrate the growth to the main shoot.

Fumigation Methods--

The plants were fumigated by circulating gas mixtures, supplied by Matheson Gas Products Inc. of East Rutherford, New Jersey, through the vessels. The gas was first circulated at a rate in excess of 1000 ml. per minute for a few minutes and then stopped. The tubing was then removed, and a flow of 120 ml. per minute was established through the tubing into ambient air. This done, the tubing was reconnected to the group of four vessels. This was repeated for each treatment. The rate of gas flow was determined daily after watering by means of a 100 ml. soap bubble flowmeter. The pressure resulting from this rate of flow into air was enough to maintain the composition of the soil atmosphere in the vessels relatively constant with no measurable outward flow. Transpiration by the tomato plants resulted in the loss of about 400 ml. of water a day. The gas was able to fill this void.

Tomato experiment 1 was designed to examine the response of tomato plants to a soil atmosphere having suppressed O_2 concentrations in conjunction with elevated concentrations of CO_2 and CH_4. This experiment consisted of twenty-one plants which were divided into three treatments with seven replicates for each. The composition of the atmospheres used for the various treatments is given in Table 8. The fumigation was started on November 11, 1976 and was discontinued on December 9, 1976.

Experiment 2 was designed to determine the effects of a soil atmosphere containing high concentrations of both methane and carbon dioxide on the growth of tomato plants compared with soil atmospheres containing only carbon dioxide or methane. This experiment consisted of twenty plants which were divided into five treatments with four replicates for each. The composition of the atmospheres used for the various treatments is given in Table

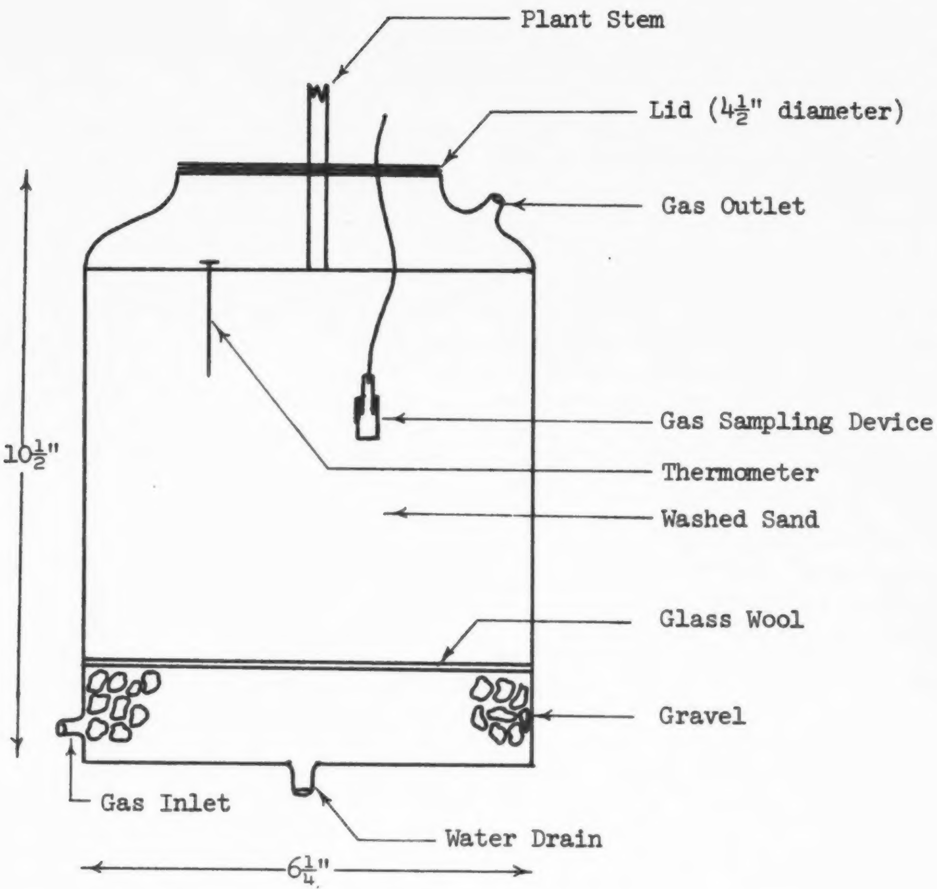
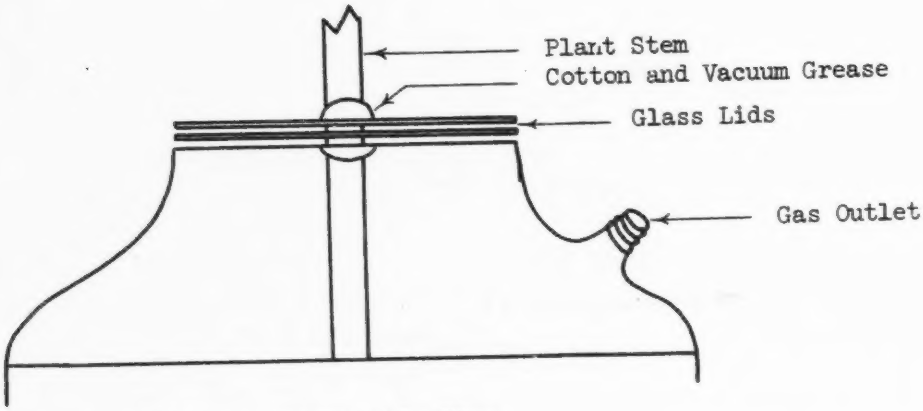
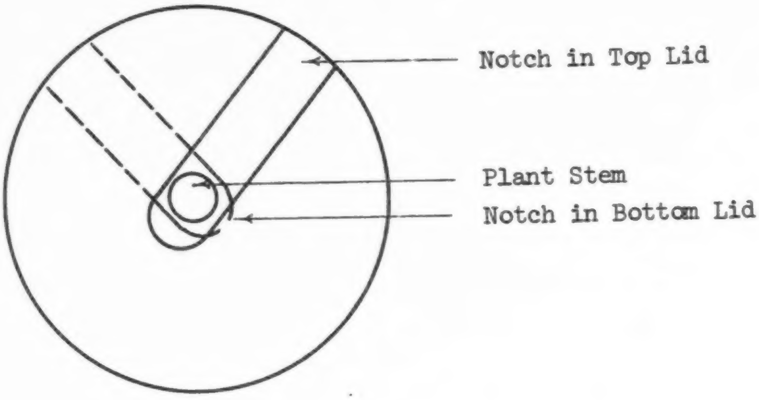

Plant Stem
Lid ($4\frac{1}{2}$" diameter)
Gas Outlet
Gas Sampling Device
Thermometer
Washed Sand
Glass Wool
Gravel
Gas Inlet
Water Drain
$10\frac{1}{2}$"
$6\frac{1}{4}$"

Figure 18. Culture vessel for tomato plant fumigations.


Plant Stem
Cotton and Vacuum Grease
Glass Lids
Gas Outlet

A. Partially Dissected Side View


Notch in Top Lid
Plant Stem
Notch in Bottom Lid

B. Top View

Figure 19. Lids for culture vessels.

9. This experiment was conducted twice; from March 22, 1977 to March 30, 1977 and again from April 19, 1977 to May 1, 1977. The first trial was of shorter duration (8 days) than the second trial which lasted twelve days.

TABLE 8. COMPOSITION OF ATMOSPHERES USED TO FUMIGATE TOMATO PLANTS IN EXPERIMENT 1

	Treatment		
	A*	B	C
$\%O_2$	21	7	7
$\%CO_2$	trace	trace	10
$\%N_2$	79	93	58
$\%CH_4$	0	0	25

* Atmospheric air

TABLE 9. COMPOSITION OF ATMOSPHERES USED TO FUMIGATE TOMATO PLANTS IN EXPERIMENT 2

	Treatment				
	A*	B	C	D	E
$\%O_2$	21	5	5	5	5
$\%CO_2$	trace	trace	40	40	trace
$\%N_2$	79	95	55	5	45
$\%CH_4$	0	0	0	50	50

* Atmospheric air

Experiment 3, was designed to determine the effects of a soil atmosphere containing high concentrations of carbon dioxide on the growth of tomato plants exposed to differing oxygen concentrations in the soil. This experiment consisted of twelve plants which were divided into three treatments with four replicates for each. Due to the results of previous experiments in which plant response to low O_2 and ambient air fumigations were identical, air controls were eliminated. The composition of the atmospheres used to fumigate the culture vessels in the various treatments is given in Table 10. The fumigation was started on October 15, 1977 and was completed on November 10, 1977.

Experiment 4, was designed to determine the effects of a soil atmosphere containing high concentrations of methane or carbon dioxide on the growth of tomato plants. This experiment consisted of sixteen plants which were divided into four treatments with four replicates for each. The composition of the atmospheres used to fumigate the culture vessels used in the various treatments is given in Table 11. The fumigation began on December 10, 1977 and was discontinued on January 9, 1978.

TABLE 10. COMPOSITION OF ATMOSPHERES USED TO FUMIGATE TOMATO PLANTS IN EXPERIMENT 3

	Treatment		
	A	B	C
%O_2	4	15	4
%CO_2	trace	30	30
%N_2	96	55	66

TABLE 11. COMPOSITION OF ATMOSPHERES USED TO FUMIGATE TOMATO PLANTS IN EXPERIMENT 4

	Treatment			
	A	B	C	D
%O_2	5	15	15	5
%CO_2	trace	20	10	trace
%N_2	95	65	75	50
%CH_4	0	0	0	45

Analytical Methods--

Growth measurements--The height of the tomato plants was determined by measuring the distance from the glass lid to the tip of the uppermost fully expanded leaf. Adventitious root development was reported only when it occurred above the lid.

Soil gas analyses--The soil atmosphere in the culture vessels was monitored with a Carle model 8500 gas chromatograph as described previously.

Nitrogen analyses--The total nitrogen content of the dry plant tissue was determined by using the Kjeldahl method, which gives a reading in mg. of N per 100 mg. of dry plant tissue (114).

SECTION 6

RESULTS

COMPOSITION OF THE SOIL ATMOSPHERES OF TWENTY COMPLETED SANITARY LANDFILLS

The majority of the CO_2 readings in the atmospheres occurred in the 0 to 4.9% category (Table 12). The majority of the O_2 readings in the atmospheres of the twenty landfills occurred in the 15 to 21% concentration category (Table 13). The combustible gas readings were concentrated in the two extreme categories, between 0 and 4.9% and greater than 25%, with the majority of the readings occurring in the 0 to 4.9% category (Table 14). This tendency of the readings to polarize at the extreme ends of the scale was also noted with respect to the CO_2 readings (Table 12). The landfills completed prior to 1966 exhibited lower average CO_2 and combustible gas readings in conjunction with higher average O_2 readings than the landfills completed since 1966 (Table 15). These differences were not statistically significant. The landfills having less than 20 feet of refuse did not exhibit any significant differences in the average concentrations of the soil atmospheric components when compared with the landfills having more than 20 feet of refuse (Table 16).

TABLE 12. PERCENT FREQUENCY OF CO_2 READINGS* OF SOIL ATMOSPHERES ON TWENTY COMPLETED SANITARY LANDFILLS

% Range	% Frequency
0 - 4.9	67.2
5 - 9.9	10.3
10 - 14.9	6.0
15 - 19.9	1.7
20 - 40+	14.7

* 116 samples at one foot depth.

TABLE 13. PERCENT FREQUENCY OF O_2 READINGS* OF SOIL ATMOSPHERES ON TWENTY COMPLETED SANITARY LANDFILLS

% Range	% Frequency
0 - 4.9	7.0
5 - 9.9	7.0
10 - 14.9	14.4
15 - 21	71.6

* 128 samples at a one foot depth.

TABLE 14. PERCENT FREQUENCY OF COMBUSTIBLE GAS READINGS* OF THE ATMOSPHERES ON TWENTY COMPLETED SANITARY LANDFILLS

% Range	% Frequency
0 - 4.9	81.6
5 - 9.9	4.6
10 - 14.9	0.6
15 - 19.9	0.5
20 - 24.9	0.3
25 - 40+	12.3

* 350 samples at a one foot depth.

TABLE 15. MEAN PERCENT CO_2, O_2 AND COMBUSTIBLE GAS AT 1-FOOT DEPTH WITH AGE OF SANITARY LANDFILL

Gas %	Completed Before 1966*	Completed After 1966**
O_2	19.0	15.2
CO_2	2.2	8.7
Combustible Gas	1.7	8.9

* Average of 5 landfills.
** Average of 15 landfills.

TABLE 16. MEAN PERCENT O_2, CO_2 AND COMBUSTIBLE GAS AT 1-FOOT DEPTH WITH DEPTH OF REFUSE IN THE SANITARY LANDFILL

Gas %	>20 Feet*	<20 Feet**
O_2	15.9	17.3
CO_2	7.3	5.3
Combustible Gas	5.0	8.9

* Average of 7 landfills.
** Average of 12 landfills.

COMPOSITION OF THE SOIL ATMOSPHERE AND ITS INFLUENCE ON THE DISTRIBUTUION OF NATIVE VEGETATION ON THE COMPLETED EDGEBORO SANITARY LANDFILL

Data for in situ measurements of gas composition on the Edgeboro Landfill by the macro-sample method are presented in Tables 17, 18, and 19 and for the micro-sample method (gas chromatography) in Table 20 and 21. At all stations monitored there was a consistent relationship between the occurrence of high levels of combustible gas and poor or no growth of vegetation. This relationship was also evident when comparing high levels of CO_2 and low levels of O_2 with poor growth of vegetation.

The four stations A, B, C, and D, monitored for the entire fifteen months (Table 2) exhibited very little fluctuation in composition of the soil atmosphere. This was also true for the stations E, F, G, and H monitored for only five months.

The cover material was significantly thicker ($P < 0.05$) where the vegetation was growing well (Table 22).

TABLE 17. PERCENT COMBUSTIBLE GAS FROM 1-FOOT DEEP TEST HOLES ON COMPLETED EDGEBORO LANDFILL

	Sampling Data					
Station	6/6/76*	7/15/76**	4/15/77*	8/10/77**	9/14/77*	9/20/77*
A	≥45	40	39	40	39	40
B	≥45	≥45	≥45	≥45	36	≥45
C	4.5	3	3.3	4.5	0.8	2.2
D	0	Wet	1.0	Wet	0	0
E	--	--	15	≥45	--	≥45
F	--	--	1	0	0	5
G	--	--	45	≥45	--	32
H	--	--	0	0	--	0.5

(continued)

TABLE 17. (continued)

Station	Sampling Data 6/6/76*	7/15/76**	4/15/77*	8/10/77**	9/14/77*	9/20/77*
I	--	--	--	--	--	0
J	--	--	--	--	--	$\geq$45
K	--	--	--	--	--	0

* Average of 4 readings. -- no reading taken.
** Average of 2 readings. Data obtained with a MSA explosimeter.

TABLE 18. PERCENT O_2 *FROM 1-FOOT DEEP TEST HOLES ON COMPLETED EDGEBORO LANDFILL

Station	7/15/76**	Sampling Date 4/15/77***	8/10/77**
A	5.0	3.5	7.5
B	6.0	7.0	2.5
C	20.0	19.4	18.75
D	wet	20.0	wet
E	---	4.2	14.5
F	---	21.0	20.0
G	---	8.5	7.5
H	---	20.5	20.5

* Readings were obtained with Bacharach, Fyrite O_2 analyzer.
** One reading.
*** Average of 2 readings.

TABLE 19. PERCENT CO_2 *FROM 1-FOOT DEEP TEST HOLE ON COMPLETED EDGEBORO LANDFILL

Station	Sampling Date 7/15/76**	 4/15/77***	 8/10/77**
A	17.0	21.0	16.0
B	18.0	25.0	34.5
C	0.5	1.0	1.5
D	wet	0.0	wet
E	---	12.5	9.0
F	---	0.5	1.5
G	---	16.0	20.0
H	---	0.0	0.0

* Readings were obtained with Bacharach, Fyrite CO_2 analyzer.
** One reading.
*** Average of 2 readings.

TABLE 20. GAS CHROMATOGRAPHIC ANALYSIS OF COMPOSITION OF SOIL ATMOSPHERE AT DEPTH OF 10-INCHES AT 6 STATIONS ON COMPLETED EDGEBORO LANDFILL, JULY 14, 1977

Station	Gas (% by volume)* O_2	 CO_2	 CH_4	 N_2
A	0.5	38.0	49.5	12.0
B	2.7	35.3	39.0	23.0
C	18.2	4.2	3.6	74.0
D	20.3	1.7	0.0	78.0
E	2.0	35.5	34.5	28.0
F	18.2	4.2	0	77.6

* Corrected to 100 percent.

TABIE 21. GAS CHROMATOGRAPHIC ANALYSIS OF COMPOSITION OF SOIL ATMOSPHERE AT DEPTH OF 10-INCHES AT 6 STATIONS ON COMPLETED EDGEBORO LANDFILL, OCTOBER 13, 1977

Station	Gas (% by volume)* O_2	 CO_2	 CH_4	 N_2
A	0.8	37.5	46.7	15.0
B	1.5	32.0	48.5	18.0
C	19.0	1.0	0.0	80.0

(continued)

TABLE 21. (continued)

	Gas (% by volume)*			
Station	O_2	CO_2	CH_4	N_2
D	20.2	1.2	2.6	76.0
E	3.0	30.0	36.0	31.0
F	18.8	2.2	1.0	78.0

* Corrected to 100 percent.

TABLE 22. DEPTH OF SOIL COVER* AT STATIONS ON EDGEBORO LANDFILL AND GROWTH STATUS OF VEGETATION

Good Vegetative Growth		Poor Vegetative Growth	
Station	Depth of Soil Cover (inches)	Station	Depth of Soil Cover (inches)
C	10.0	A	5.1
F	10.1	B	7.4
D	8.2	E	3.9
H	9.5	G	3.0
K	6.7	J	3.9
I	6.5		
Mean	8.5**	Mean	4.7

* Each value is the mean of 5 observations.

** Significantly greater ($P < 0.05$).

SPECIES SCREENING EXPERIMENT

Relative Viability of Plants

Sixty-two trees died on the experimental and control plots during this study: 38 on the experimental and 24 on the control plot (Table 23).

TABLE 23. NUMBER OF TREE DEATHS IN SCREENING EXPERIMENT BETWEEN 1976 AND 1977

Species	Summer 1976		Winter 1976-77		Summer 1977	
	Exp.	Control	Exp.	Control	Exp.	Control
Rhododendron	2	2	2	4	6	4
Hybrid Poplar	0	1	1	0	6	2
Mixed Hybrid Poplar	0	2	0	5	0	0
Euonymus	0	0	5	0	1	0
Black Gum	4	1	0	1	1	0
Sweet Gum	1	0	1	0	2	1
Weeping Willow	4	0	0	0	0	0
Red Maple	0	0	0	0	1	0
Ginkgo	0	1	0	0	0	0
Bayberry	0	0	0	0	0	1
Japanese Yew	0	0	0	0	0	1
Norway Spruce	0	0	0	0	1	0
	11	5	9	10	18	9
	16		19		27	

Relative Growth of Surviving Plants

The interpretation of whether a particular species grew significantly better on the control or on the experimental plot depended upon the tree variable measured (Table 24). On the basis of three or more of these dependent (tree) variables, the majority of species grew significantly better on the control than on the experimental plot.

Shoot length was the only tree variable measured both in 1976 and 1977. With respect to shoot length, twelve species on the control plot appeared to grow better during the 1977 season than in 1976; whereas on the experimental plot, only seven species apparently grew better during the 1977 growing season than they did during 1976. This is indicated by the average shoot length calculated for each species - plot combination for each year (Table 24) and reflects the stress on the trees growing on the experimental plot.

TABLE 24. MEAN VALUES FOR THE FIVE TREE VARIABLE FOR EACH SPECIES ON THE EXPERIMENTAL AND CONTROL PLOTS

Species	Plot	Root Biomass (mg)	Leaf Wt. (g)	Visual Obs.	Basal Area % increase [1]	Shoot Length (cm) 1976	Shoot Length (cm) 1977
Red Maple	Cont.	1270	6.4**	4.4*	69.2	20.6	45.5
	Exp.	579	2.4	2.8	39.0	21.6	15.2
Euonymus	Cont.	1807**	1.2**	3.5**	44.5	18.8**	13.2*
	Exp.	691	0.2	1.1	28.9	15.2	3.8
Green Ash	Cont.	1416	10.5**	4.6**	57.1**	30.4	15.5**
	Exp.	681	4.3	3.1	23.8	34.0	5.8
Ginkgo	Cont.	958**	0.36	1.1	12.6	17.8	0.8
	Exp.	477	0.35	1.3	7.4	23.3*	0.8
Honey Locust	Cont.	1370	23.9 **	4.7**	94.7**	10.4	68.6**
	Exp.	821	2.8	1.7	25	11.7	5.1
Sweet Gum	Cont.	1522**	7.6**	4.9**	198 **	12.7	35.3
	Exp.	432	3.7	2.1	86	12.2	17.0
Bayberry	Cont.	868**	2.0	3.4	66.3	10.4	20.3
	Exp.	294	2.3	4.2	46.7	7.4	17.0
Black Gum	Cont.	1098	2.4	4.2	178	7.9	25.6
	Exp.	524	1.8	2.6	211	8.6	20.8
Norway Spruce	Cont.	689	0.37	3.9	34.3	12.2	4.8
	Exp.	497	0.34	2.8	35.6	10.9	6.1
Hybrid Poplar	Cont.	895*	8.0 **	2.5	696	35.0**	85.8
	Exp.	335	1.0	1.3	16	20.0	12.7
Mixed Poplar	Cont.	270	34.0	4.1	4362	25.4	134.1
	Exp.	592	24.0	4.2	1178	31.0	92.9
American Sycamore	Cont.	1375	11.4	4.9**	53.0**	22.6	42.2
	Exp.	778	7.8	2.9	33.5	20.6	43.7
White Pine	Cont.	1829	2.3	4.3**	52.0	20.8	10.9
	Exp.	961	1.7	3.4	40.0	15.2	7.9
Black Pine	Cont.	1281	15.9*	4.9**	68	18.8	19.8**
	Exp.	907	12.0	3.8	65	19.3	14.5
Pin Oak	Cont.	1047	4.5	4.8*	115 *	13.7	23.1**
	Exp.	628	3.6	3.8	76	12.4	13.5
Weeping Willow	Cont.	1864**	11.6*	4.5**	114 **	69.6	217.2**
	Exp.	429	3.9	1.0	.17	75.2	65.6
American Basswood	Cont.	1865**	1.0	2.7	28.8 **	19.8	18.5**
	Exp.	713	1.2	2.7	19.2	19.0	9.9

[1] - % increase from March to September

(continued)

TABLE 24. (continued)

Species	Plot	Root Biomass	Leaf Wt.	Visual Obs.	Basal Area	Shoot Length (cm)	
		(mg)	(g)	% increase [1]		1976	1977
Japanese Yew	Cont.	1087	0.98	4.6	19.3**	11.9	12.2
	Exp.	572	0.50	4.3	45	12.7	19.6
Rhododendron	Cont.	0	0	0	0	8.4*	0.0
	Exp.	0	0	0	0	6.1	0.0

* Significant difference between control and experimental plot @ 95% C.L.
** Significant difference between control and experimental plot @ 99% C.L.

The results of Student's "t" tests for the dependent variables (i.e. root biomass, shoot length, leaf weight and basal area) comparing experimental with control plot indicated that black gum exhibited the least difference in growth between the experimental and control plot (Table 25). Rhododendron had the poorest growth of all species in that all replicates on both plots succumbed by the end of the winter of 1976-1977, presumably from the abnormally cold temperatures.

TABLE 25. RELATIVE TOLERANCE OF SPECIES TO LANDFILL CONDITIONS

Rank a	Species	Σ "t" Statistics b
1	Black Gum	2.66
2	Norway Spruce	3.22
3	Ginkgo	4.95
4	Black Pine	6.59
5	Bayberry	6.62
6	Mixed Poplar	8.13
7	White Pine	8.94
8	Pin Oak	8.96
9	Japanese Yew	8.98
10	American Basswood	9.48
11	American Sycamore	10.66
12	Red Maple	10.95
13	Sweet Gum	12.62
14	Euonymus	14.25
15	Green Ash	14.87
16	Honey Locust	15.05
17	Hybrid Poplar	20.33
18	Weeping Willow	21.20
19	Rhododendron	All plants died

(continued)

TABLE 25. (continued)

a. Rank 1 = the best growth when experimental plot is compared to the control plot, i.e. most tolerant of landfill conditions.

b. Σ"t" = the sum of the "t" statistics for shoot length in 1976; leaf weight, basal area increase, root biomass and shoot length in 1977 comparing the experimental area with the control.

Soil Variables

Measurements of numerous soil variables throughout the study were made in order to characterize the nature of the stress to which the plants were subjected on the experimental plot and to compare the values for these variables with those in the control plot (Table 26). The mean carbon dioxide, methane and temperature were significantly greater (99% C.L.) and the oxygen and moisture content significantly lower on the experimental plot than on the control plot.

The calcium content (Table 26) was not significantly different between plots immediately after fertilization in June 1977; however, by November, the experimental plot contained less calcium than the control (99% C.L.). The pH was significantly lower on the control before and after fertilization (99% C.L.). There were no other significant differences for any of the other measured nutrients between plots.

The soil textures (Table 26) were different (99% C.L.) between the two plots with the experimental plot consisting of 82.8% sand while the control plot contained 74.0% sand.

The moisture content of the experimental plot and control plots over time during the summer 1977 is represented in Figure 20. For every date the control plot shows a greater moisture content than the experimental plot.

TABLE 26. MEAN VALUES FOR SOIL VARIABLES ON EXPERIMENTAL AND CONTROL PLOTS IN 1977

Soil Variables	Experimental	Control
% O_2	17.8	19.7*
% CO_2	5.5*	1.2
% CH_4	0.9*	0.0
Temperature °F	66.2*	64.3
% Moisture Content	8.1	11.0*
pH	5.0	4.8
Mg	141	143
P	106	97

(continued)

TABLE 26. (continued)

Soil Variables	Experimental	Control
K	252	283
CA	266	229
COND	29	32
NO_3	42	74
NH_4	201	271
Organic Matter	9.6	10
Fe	54.7	82
Cu	196	210
Zn	579	465
Mn	301	385
B	67	62
Sand	82.8	74.0
Silt		
Clay		

* Differences between experimental and control plots significant at 99% C.L.

The average nitrate (NO_3^-) and ammonium (NH_4^+) nitrogen for the experimental and control plots are given in Table 27 for samples collected on three separate dates in 1976 and 1977. There was no significant difference between plots for NH_4^+ nitrogen on any of the three dates in spite of the fact that, in June 1977, the NH_4^+ on the control was much greater in concentration than on the experimental plot. A single very high reading on the experimental plot was the cause for this large difference.

TABLE 27. MEAN VALUES FOR NITRATE AND AMMONIUM NITROGEN ON EXPERIMENTAL AND CONTROL PLOTS

Date	Experimental a			Control b		
	NO_3 lbs/A	NH_4 lbs/A	Ratio NO_3:NH_4	NO_3 lbs/A	NH_4 lbs/A	Ratio NO_3:NH_4
October '76	6.0	58.3	0.10	10.5	48.5	0.22
June '77	67.1	370.0	0.18	103.2	587.1	0.18
November '77	16.8	10.8	1.56	39.5	11.5	3.43*

a. Each number is the average of 7 separate measurements.
b. Each number is the average of 4 separate measurements.
* Significantly greater than experimental plot (95% C.L.).

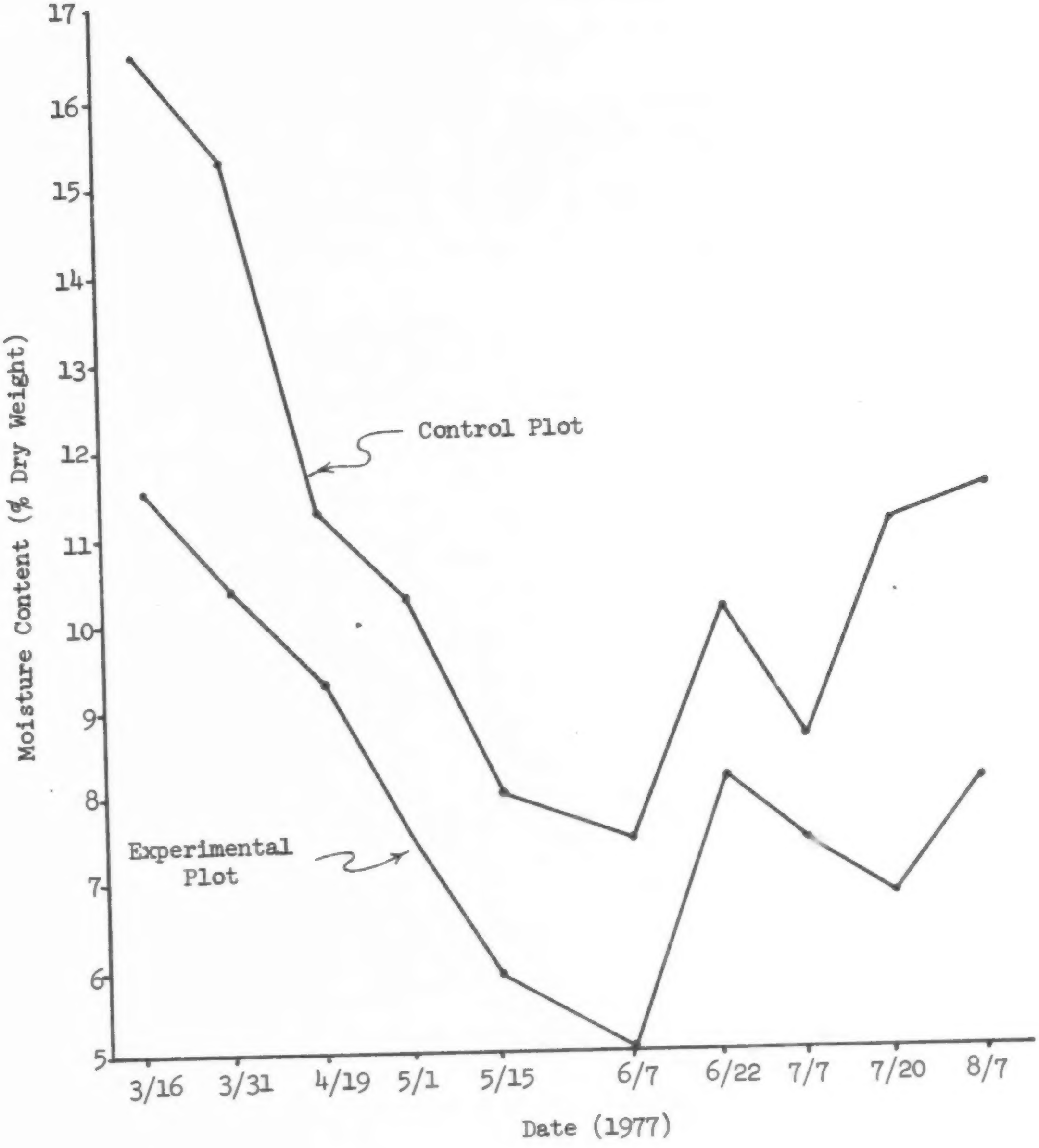


Figure 20. Soil moisture content of experimental and control plots.

The NO_3^- nitrogen content in the experimental plot was statistically similar to that in the control after fertilization in June 1977; however, by November, NO_3^- was significantly lower in the experimental plot (95% C.L.). This resulted in a significantly lower NO_3^-:NH_4^+ ratio in the experimental plot than in the control.

Despite the anticipated variability in the independent soil variables from one sampling location to another, and from one sampling date to the next on the control plot, the variability on the experimental plot was far greater than on the control particularly for oxygen, carbon dioxide and methane. This is reflected in the coefficients of variation calculated for each independent soil variable in both plots (Table 28).

TABLE 28. COEFFICIENTS OF VARIATION FOR SOIL VARIABLES ON EXPERIMENTAL AND CONTROL PLOTS

Soil Variables	Experimental	Control
O_2	26.42**	4.02
CO_2	117.34**	36.29
CH_4	388.86**	0.00
Temperature	13.47	12.49
Moisture Content	28.19	29.07
pH	5.63	4.11
Mg	66.86	60.91
P	50.09	77.90
K	44.50	36.97
CA	115.69	119.73
COND	54.00	63.32
NO_3	73.69	59.32
NH_4	104.71	133.57
Organic Matter	77.85	72.17
Fe	149.87	125.19
Cu	106.65	105.84
Zn	51.19	60.22
Mn	82.83	71.53
B	48.25	65.15

** Significant at 99% confidence level.

Root System Profiles

The extent of vertical root penetration for plants growing on the experimental landfill plot was found to be approximately 6-8 inches with the root biomass in the top 6 inches of soil. The data indicated that the roots of plants growing on the control plot penetrated 2-4 inches (or 1.5 times) deeper than on the experimental plot (Table 29).

TABLE 29. DEPTH OF ROOT PENETRATION ON EXPERIMENTAL AND CONTROL PLOTS [a]

Species	Experimental Plot	Control Plot
Basswood	6"	9" *
Sycamore	5"	7"
Sweet Gum	6"	10" *
Black Gum	4"	7"
Black Pine	5"	8" *

a. Average of 4 trees.
* Significant difference between plots @ 95% C.L.

GAS-BARRIER TECHNIQUES

Relative Viability of Plants

All plants in the gas-barrier techniques broke bud soon after planting in the spring of 1976. During the following growing season all ten plants (6 American basswood and 4 Japanese yew) on the clay/vents trench died as well as ten Japanese yew scattered on the remaining barrier techniques (Table 30). All remaining plants survived the winter 1976-1977, however, by the end of the 1977 growing season, six plants had died (4 of these were in trench-clay/vents where 6 plants had died the previous year).

Relative Growth of Surviving Plants

Tree data collected in 1976 and 1977 from the five experimental gas-barrier techniques and the experimental screening area (which serves as a control for the barrier techniques) for American basswood and Japanese yew are given in Table 31. For American basswood, the gravel/plastic/vents trench and clay barrier mound on landfill supported significantly better (99% C.L.) growth than did the experimental screening area which had no special treatment and represented typical landfill conditions. This was true for all the dependent (tree) variables measured excluding root biomass. The variability in root biomass among the basswood trees within each of the planting techniques is reflected in the relatively large variance components among trees compared to those among techniques (Table 32). Because the variability among trees was greater than the variability among barrier techniques, no statistical differences were detected between barrier techniques and experimental screening area despite the large difference in mean root biomass. However, the measurements for root biomass for the gravel/plastic/vents trench, the clay barrier trench and the clay barrier mound fall at the high end of the range of values for all techniques (Table 32).

Japanese yew showed no significant differences between the barrier techniques and the experimental screening area. The variance components for Japanese yew within the barrier techniques were relatively large compared to among techniques for shoot length, leaf weight and root biomass illustrating the great variability among trees compared to the variability among barrier

TABLE 30. OBSERVATION OF DEAD TREES ON EXPERIMENTAL AND CONTROL GAS-BARRIER TECHNIQUES

Seasons					
1976 Growing Season		1976-1977 Winter		1977 Growing Season	
Experimental a	Control a	Experimental	Control	Experimental	Control
American Basswood 216 217 218 219 220 221 Japanese Yew 223 225 226 227 231 233 234 238 239 240 241	American Basswood 192 Japanese Yew 210	No trees died	No trees died	American Basswood 216 217 219 220 Japanese Yew 228 229	No trees died

a. All these plants were replaced in October 1976.

techniques (Table 32), resulting in no significant difference between any of the techniques and the experimental screening area (Table 31).

Soil Variables

The average nitrate (NO_3^-) and ammonium (NH_4^+) nitrogen content in each barrier technique is given in Table 33 for samples collected on two separate dates in 1977. The $NO_3^-:NH_4^+$ ratios in June for all techniques were relatively similar, however, by November, the $NO_3^-:NH_4^+$ ratio was more than two times lower in the clay/vents trench than any other technique. There were no other discernable nutrient trends other than a small decrease in the manganese concentration in the clay/vents trench compared to a relatively large decrease in all other barrier techniques, resulting in a high manganese (45 ppm) concentration by November (Table 33) in the clay/vents trench.

The values for soil oxygen, carbon dioxide, methane, moisture content and bulk density are given in Table 34 for each gas-barrier technique. These data show that the gravel/plastic/vents trench and the two mounds on the experimental plot contained no excessive amounts of carbon dioxide and no methane and that the oxygen concentration was 19.8% or greater. However, carbon dioxide and methane from refuse decomposition contaminated the clay/vents trench and the clay trench. The oxygen concentration in these two latter trenches was also significantly lower than in the control and in the

TABLE 31. MEAN VALUES FOR DEPENDANT TREE VARIABLES FOR EACH GAS-BARRIER TECHNIQUE ON EXPERIMENTAL AREA

Planting Technique	Species	Root Biomass (mg)	Basal Area % (increase)	Visual Obs.	Leaf Weight (g)	Shoot Length 1976 (inches)	Shoot Length 1977 (inches)
Trench-Plastic/ Vents/Gravel	Jap. Yew	516	17.0	5.0	1.24	5.2	2.61
	Basswood	800	73.3*	4.5*	3.97*	12.41*	8.98*
Trench-Clay/ Vents	Jap. Yew	74	9.3	2.0	0.41	0.52	2.43
	Basswood	153	0.0	0.0	0.02	1.06	.66
Trench-Clay/ No Vents	Jap. Yew	616	26.0	4.0	0.59	5.1	2.96
	Basswood	1069	23.9	3.5	2.21	7.19	5.58
Mounds-No Clay	Jap. Yew	1051	14.0	3.5	0.64	6.9	1.84
	Basswood	622	31.3	4.5*	1.89	10.98*	6.66
Mound-Clay	Jap. Yew	1062	6.2	2.5	0.85	7.1	2.78
	Basswood	930	60.0*	4.5*	3.40*	12.15*	8.52*
Experimental Screening Area	Jap. Yew	572	45.0	4.3	10.98	5.0	2.17
	Basswood	644	26.8	2.5	1.04	7.46	3.84

* Grew significantly better than the experimental screening area @ 99% C.L.

TABLE 32. VARIANCE COMPONENTS FOR AMERICAN BASSWOOD AND JAPANESE YEW FOR THREE TREE VARIABLES

Shoot Length			
American Basswood		Japanese Yew	
Source of Variation	Variance Components	Source of Variation	Variance Components
Among techniques	73.20	Among techniques	10.59
Among trees	6.53	Among trees	21.50
Among measurements	5.79	Among measurements	2.32

Leaf Weight			
American Basswood		Japanese Yew	
Source of Variation	Variance Components	Source of Variation	Variance Components
Among techniques	15.08	Among techniques	0.08
Among trees	0.68	Among trees	0.36
Among measurements	0.79	Among measurements	0.08

Root Biomass			
American Basswood		Japanese Yew	
Source of Variation	Variance Components	Source of Variation	Variance Components
Among techniques	573,181	Among techniques	57,832
Among trees	916,160	Among trees	286,432

TABLE 33. NITRATE NITROGEN, AMMONIUM NITROGEN AND MANGANESE CONTENTS OF SOIL IN THE BARRIER TECHNIQUES

	Experimental Plot										Control Plot			
	Trench-gravel, plastic, vents		Trench-clay vents		Trench-clay no vents		Mound-no clay		Mound clay		Trench		Mound	
	June 77	Nov. 77	June 77	Nov. 77	June 77	Nov. 77	June 77	Nov. 77	June 77	Nov. 77	June 77	Nov. 77	June 77	Nov. 77
NO_3 lbs/A	120.0	20.0	61.0	12.0	50.0	12.0	57.0	14.0	46.0	40.0	62.0	36.0	134.0	84.0
NH_4 lbs/A	620.0	8.0	395.0	12.0	280.0	4.0	580.0	2.0	340.0	16.0	360.0	6.0	560.0	22.0
NO_3:NH_4 ratio	0.19	2.5	0.15	1.0	0.18	3.0	0.10	7.0	0.14	2.22	0.17	6.0	0.24	3.80
Mn ppm	90.0	6.5	55.0	45.0	50.0	6.0	50.0	8.5	72.5	11.0	44.5	12.5	77.5	14.0

other three techniques on the experimental plot (99% C.L.).

TABLE 34. MEAN SOIL VARIABLE LEVELS IN THE GAS-BARRIER TECHNIQUES

	Gas-Barrier Techniques	Oxygen %Volume	Carbon Dioxide %Volume	Methane %Volume	Moisture Content % Dry Weight	Bulk Density
Experimental Plot	Gravel/Plastic Vents Trench	19.8c*	1.3a	0.0a	9.0b	1.29a
	Clay/Vents Trench	4.3a	22.8c	11.8c	11.0c	1.42a
	Clay Trench	16.3b	7.0b	0.7b	8.4b	1.67b
	Mound	20.3c	0.8a	0.0a	7.3a	1.34a
	Clay Mound	20.3c	0.8a	0.0a	7.5a	1.45a
Control Plot	Trench	19.6c	1.2a	0.0a	10.5c	1.73b
	Mound	19.4c	1.2a	0.0a	10.7c	1.45b

* Means in a column followed by different letters are statistically different at $P < 0.01$.

The moisture content of the soil in the experimental techniques was generally lower than on the control; however, the highest moisture content is in the clay/vents trench. In addition, analysis of variance showed that the soil in the two mounds on the experimental plot had a significantly lower moisture content than any of the other barrier techniques. Analysis of variance of bulk density showed that the values in the clay trench on the experimental plot as well as the trench on the control plot were significantly higher than in any other techniques (99% C.L.).

Statistical Analysis of the Effect of Soil Variables on Tree Variables

Multiple regression analysis of American basswood shoot length data shows a correlation with the linear responses of carbon dioxide, lowest oxygen, highest temperature, bulk density and moisture content, $R^2=53\%$. The general multiple linear regression model given in equation 1 becomes the estimated multiple

$$Y = B_0 + B_1 X_1 + B_2 X_2 + \ldots + B_u X_u + C_i \qquad (1)$$

regression equation for basswood shoot length in equation 2.

$$Y = 45.24 - 0.32 \text{ lowest oxygen} - 0.57 \text{ carbon dioxide} - 0.24 \text{ highest temperature} - 12.34 \text{ bulk density} + 0.78 \text{ moisture content.} \qquad (2)$$

Addition of the quadratic, reciprocal and interactive effects of these variables did not change the coefficient of determination (R^2).

Multiple regression analysis of basswood leaf weight shows a correlation with the linear responses of temperature and bulk density, $R^2 = 41\%$ according to equation 3.

$$Y = 37.86 - 0.37 \text{ temperature} - 6.58 \text{ bulk density} \qquad (3)$$

When the quadratic, reciprocal and interactive effects of these variables were added into the analysis, an increase in R^2 of 22% was obtained with the equation

$$Y = 37.69 - 0.23 \text{ highest temperature} - 10.12 \text{ bulk density} - 0.10 \text{ (moisture content x carbon dioxide)} - 1.42/CO_2 +4 \qquad (4)$$

giving an $R^2 = 63\%$.

When the tree response root biomass was regressed onto the ten soil variables, it was found to correlate linearly with temperature, bulk density and moisture content, $R^2 = 39\%$ according to the equation

$$Y = 15395.87 - 222.17 \text{ temperature} - 1129.52 \text{ bulk density} + 269.65 \text{ moisture content.} \qquad (5)$$

The addition of quadratic, reciprocal and interactive effect of these variables did not change the coefficient of determination.

Multiple regression analysis of basswood basal area increment data shows carbon dioxide and bulk density to be linearly correlated with the response basal area $R^2 = 48\%$ as seen in equation 6.

$$Y = 141.48 - 2.42 \text{ carbon dioxide} - 59.07 \text{ bulk density.} \qquad (6)$$

Examination of the quadratic, reciprocal and interactive effects produced an increase of 5% in the coefficient of determination to $R^2 = 53\%$ (see equation 7).

$$Y = 169.05 - 69.60 \text{ bulk density} - 2.07 \text{ (bulk density x carbon dioxide)} - 9.60/CO_2+4 \qquad (7)$$

THE EFFECT OF CARBON DIOXIDE AND METHANE IN THE ROOT ZONE OF TWO MAPLE SPECIES

At the termination of the 48-day experiment to compare the effects of simulated landfill gases with those of flooding on two maple species, both red and sugar maple trees fumigated with CO_2 and CH_4 were in noticeably worse condition than the controls. The main symptoms were chlorosis and abscission of the lower leaves (Table 35). The flooded sugar maples began to lose their leaves by the 11th day of treatment and defoliation was complete by the 20th day. The red maples still had most of their leaves at the termination of the experiment on the 48th day, however, the leaves which still remained attached were chlorotic. All the red maples that were flooded exhibited adventitious root development below or just above the surface of the water and swelling of the lenticels which were exuding a soft textured white substance.

TABLE 35. NUMBER OF MAPLE SEEDLINGS* EXHIBITING VARIOUS GROWTH CONDITIONS AT TERMINATION OF EXPERIMENT

	1 $CO_2 + CH_4$		2 Air		3 Flooding	
Condition	Red	Sugar	Red	Sugar	Red	Sugar
Healthy	1	1	6	8	0	0
Chlorotic						
Lower third of tree	5	1	4	2	3	0
Lower half of tree	2	4	0	0	5	0
> half of tree	2	4	0	0	2	0
Defoliated	0	0	0	0	0	10
Adventitious	0	0	0	0	10	0

* 10 seedlings in each treatment.

The rate of transpiration which is inversely related to stomatal diffusive resistance for the sugar maples fumigated with CO_2 and CH_4 (Treatment 1) was found to be significantly less than the control on day-24 (Tables 36 & 37). The red maple seedlings fumigated with CO_2 and CH_4 showed no significant difference in transpiration from the control at any time during the experiment (Table 36 & 37). The sugar maples grown in flooded soil showed a significant decrease in transpiration rate on the 3rd day of the treatment, whereas the red maples which were flooded did not show a decrease in transpiration until day-42 of the experiment (Tables 36 & 37).

The composition of the soil atmosphere in the garbage cans fluctuated during the experiment. These data are given in Figures 21, 22, 23 and 24.

TABLE 36. MEAN STOMATAL RESISTANCE (SEC/CM)* OF RED AND SUGAR MAPLE SEEDLINGS IN VARIOUS TREATMENTS

	Treatment					
	1		2		3	
Date	CO_2 + CH_4		Air		Flooding	
1977	Red	Sugar	Red	Sugar	Red	Sugar
8/9	6.5	N R	N R	7.5	6.5	8.5
8/10	13.5	16.0	11.0	18.5	N R	N R
8/12	9.5	9.0	9.5	11.0	14.0	66.5
8/15	8.0	7.5	7.5	7.0	7.5	26.0
8/18	7.5	14.5	11.0	15.5	16.5	81.0
8/21	7.5	8.0	8.0	8.5	6.0	109.0
8/23	8.5	12.0	9.5	13.0	11.0	120.0
8/29	9.0	15.5	9.5	9.0	13.0	N L
9/2	7.5	21.0	6.5	7.5	7.5	N L
9/8	13.5	89.5	13.5	17.0	17.5	N L
9/21	13.5	60.5	12.0	11.0	24.0	N L
9/27	19.5	49.0	17.5	19.5	28.5	N L

N R No reading.
N L No leaves.
* Each value is the mean of 4 or 10 readings per 10 trees.

TABLE 37. STOMATAL RESISTANCE* OF MAPLE SEEDLINGS FOR TREATMENTS 1 AND 3 RECORDED AS PERCENT OF CONTROL

	Treatment			
	1		3	
Date	CO_2 + CH_4		Flooded	
1977	Red	Sugar	Red	Sugar
8/10	122.7	86.4	N R	N R
8/12	100.0	81.8	147.1	604.5**
8/15	106.6	106.1	100.0	328.5**
8/18	63.6	93.4	150.0	522.5**
8/21	93.8	94.1	75.0	1282.3**
8/23	89.5	92.3	115.7	882.3**
8/29	94.7	172.2	136.7	N L
9/2	115.3	280.0**	115.3	N L
9/8	100.0	526.4**	129.6	N L
9/21	112.5	550.2**	200.0	N L
9/27	111.3	251.2**	162.8	N L

(continued)

TABLE 37. (continued)

N R No readings.
N L No leaves.
* Each value is the mean of 4 or 10 readings.
** Statistically significant increase ($P < 0.01$).

EFFECT OF CO_2 AND CH_4 ON THE GROWTH OF TOMATO PLANTS IN SAND SOLUTION CULTURE

Experiment 1

The average composition of the soil atmosphere in the culture vessels for each treatment is given in Table 38. No statistically significant difference was found between the three treatments in terms of total change in height, total dry weight of the leaves or total nitrogen content of the leaf tissue (Table 39). Four of these plants exhibited a reddening of the veins on the intermediate-aged leaves which had been fully expanded at the start of the fumigation. This symptom was not observed on any of the plants treated with low O_2 or air (Treatments A & B). All the plants receiving high CO_2 and CH_4 concentrations exhibited adventitious root development on the stems above the glass lids.

Temperatures in the vessels ranged from a low of 65°F to a high of 81°F during the experimental period.

TABLE 38. MEAN PERCENT COMPOSITION* OF THE CULTURE VESSEL ATMOSPHERES IN EXPERIMENT 1

	Treatment		
Gas %	A	B	C
O_2	20.7	12.2	10.5
CO_2	1.1	1.3	7.2
N_2	78.2	86.5	62.3
CH_4	0.0	0.0	20.0

* Mean of 35 to 40 observations, corrected to 100 percent.

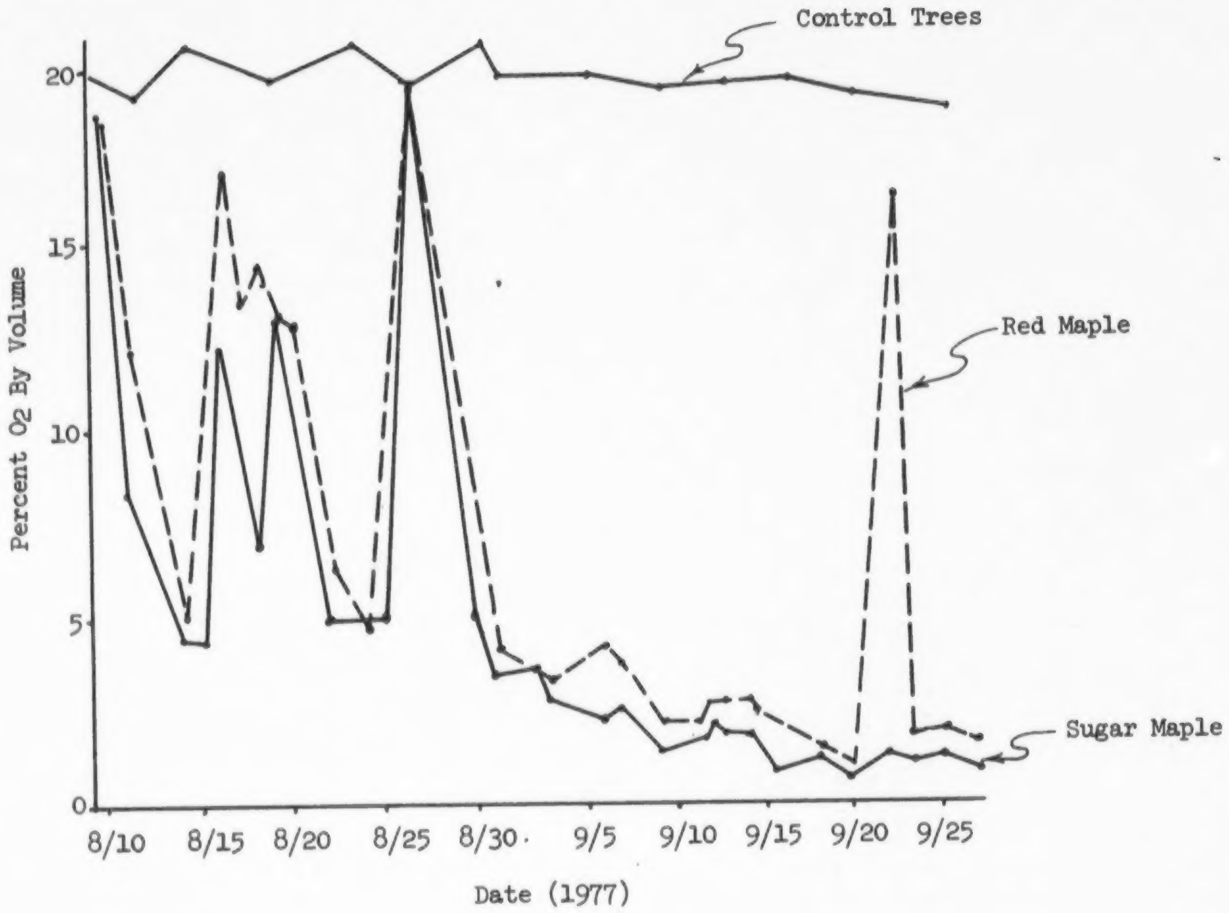


Figure 21. Mean percent O_2 at 7" depth in fumigated trash cans.

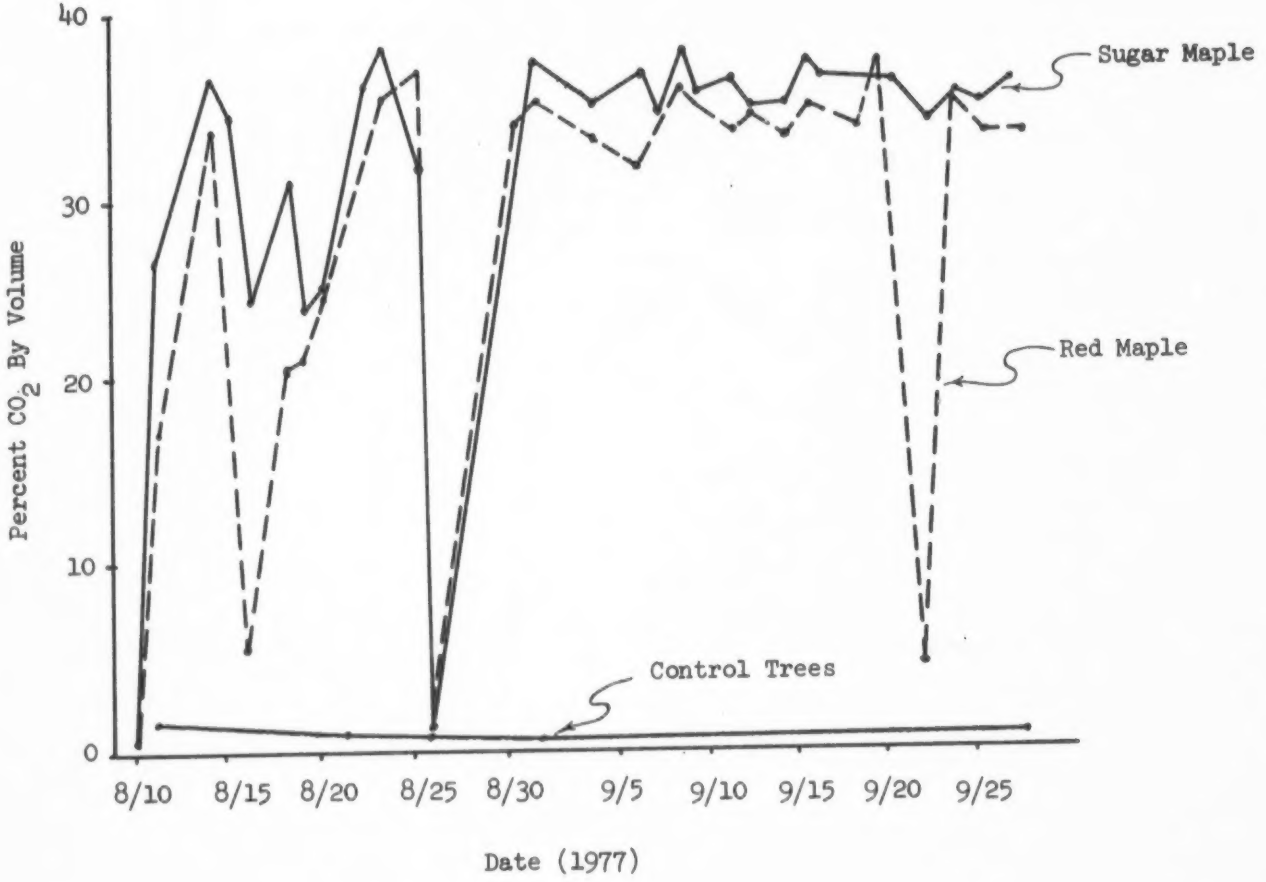


Figure 22. Mean percent CO_2 at 7" depth in fumigated trash cans.

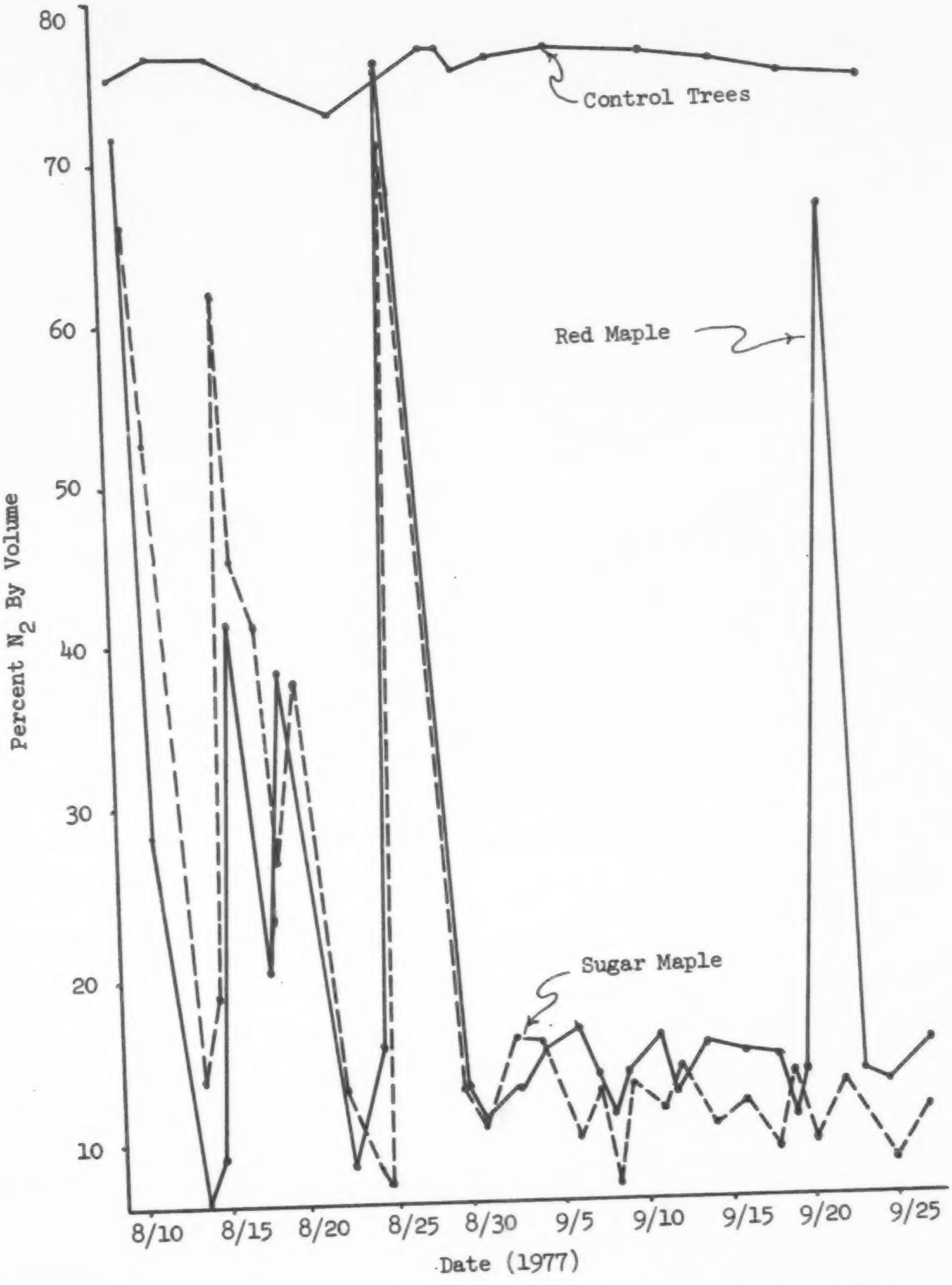


Figure 23. Mean percent N_2 at 7" depth in fumigated trash cans.

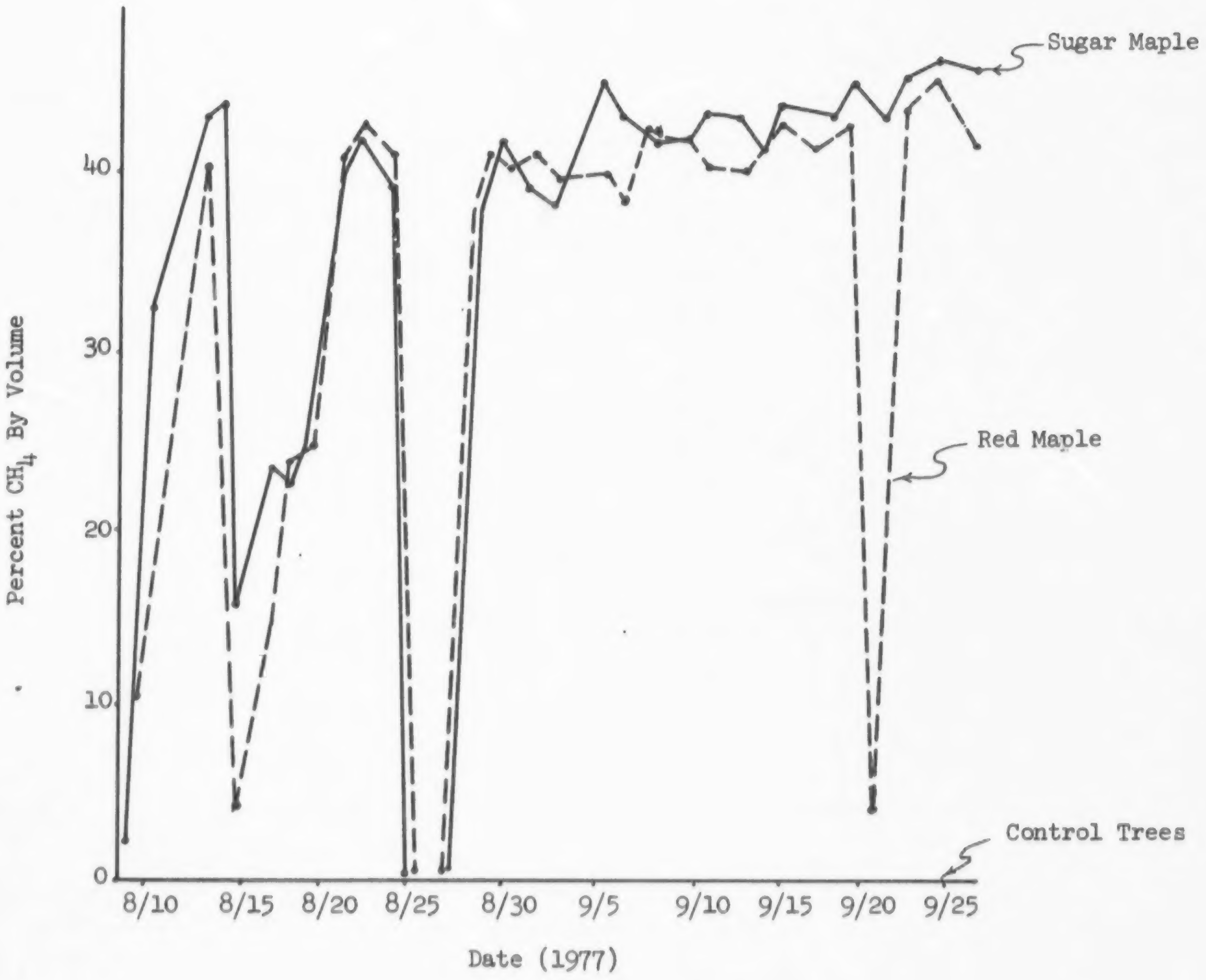


Figure 24. Mean percent CH_4 at 7" depth in fumigated trash cans.

TABLE 39. TOTAL INCREASE IN HEIGHT, FOLIAR DRY WEIGHT, AND TOTAL NITROGEN CONTENT OF THE LEAVES OF TOMATO PLANTS* AT THE TERMINATION OF EXPERIMENT 1

	Treatment		
	A	B	C
Total Nitrogen (%)	1.9	1.6	1.9
Total dry weight (g)	13.1	12.4	13.1
Total increase in height (cm)	16.7	10.2	16.7

* Each value is the mean of 7 replicates.

Experiment 2

The average composition of the culture vessel substrate atmospheres for each treatment in the two trials of this experiment are given in Tables 40 and 41.

TABLE 40. MEAN PERCENT COMPOSITION* OF THE CULTURE VESSEL ATMOSPHERES IN EXPERIMENT 2, (8-DAY FUMIGATION)

	Treatment				
Gas %	A	B	C	D	E
O_2	20.0	6.9	6.6	6.4	6.3
CO_2	0.6	0.7	34.2	39.5	0.9
N_2	79.4	92.4	59.2	7.6	47.6
CH_4	0.0	0.0	0.0	46.5	45.2

* Mean of 20 to 25 observations, corrected to 100 percent.

TABLE 41. MEAN PERCENT COMPOSITION* OF THE CULTURE VESSEL ATMOSPHERES IN EXPERIMENT 2, (12-DAY FUMIGATION)

	Treatment				
Gas %	A	B	C	D	E
O_2	20.0	6.7	6.7	5.2	5.0
CO_2	0.5	0.4	35.1	39.2	1.8
N_2	79.5	92.9	58.2	9.8	49.9
CH_4	0.0	0.0	0.0	45.8	43.3

* Mean of 30 to 33 observations, corrected to 100 percent.

The plants that were treated with air or low O_2, but no CH_4 or CO_2 (Treatments A and B) grew significantly better than did the plants receiving high CO_2 with or without CH_4 (Treatments C and D). This was true for both the 8-day and 12-day trials of the experiment and was evidenced by greater nitrogen content of the leaf tissue, increased height of the plants and greater dry weight of the leaf tissue (Tables 42 and 43). The visual appearance of the plants also bore out this relationship. The plants receiving high concentrations of CO_2 with or without CH_4 (Treatments C and D) began to decline after three days of treatment. The symptoms observed were a swelling of the stem accompanied by the formation of adventitious roots which became more pronounced as the treatments continued. The leaves first became chlorotic, then completely yellow and finally, necrotic. This decline progressed upwards on the stem for the duration of the experiment.

At the termination of the 8-day trial the plants receiving air or low O_2 (Treatments A and B) were in the same condition as the plants receiving CH_4 and no CO_2 (Treatment E). This relationship was evident in terms of the parameters measured and the visual appearance of the plants. During the second trial (12 days) the plants receiving CH_4 and no CO_2 were in the same condition as the plants receiving air or low O_2 after eight days of treatment but by the twelfth day they had gone into a rapid decline. This decline was believed to have been caused by lower O_2 concentrations in the vessels brought about by a build-up of methane-utilizing bacteria in the substrate. The O_2 levels had fallen below 2% in Treatment E after eight days of treatment concomitant with the decline of the plants. Oxygen depletion was not observed in any of the other treatments.

During the first trial the temperatures in the greenhouse ranged from 68°F to 77°F and in the vessels from 70°F to 81°F. During the second trial the temperature in the greenhouse ranged from 75°F to 88°F and in the vessels, from 73°F to 90°F. No consistent temperature differences were observed between the treatments.

TABLE 42. TOTAL INCREASE IN HEIGHT, FOLIAR DRY WEIGHT, AND TOTAL NITROGEN CONTENT OF THE LEAVES OF TOMATO PLANTS* AFTER 8-DAYS OF FUMIGATION IN EXPERIMENT 2

	Treatment				
	A	B	C	D	E
Total nitrogen (%)	2.1a	1.7b	1.6b	1.5b	2.1a
Total dry weight (g)	8.7a	8.7a	2.7b	3.0b	9.0a
Total increase in height (cm)	16.5a	15.3a	4.1b	4.7b	15.5a

* Mean of 4 replicates.
All values in row followed by an a are greater than values followed by a b. ($P < 0.01$).

TABLE 43. TOTAL INCREASE IN HEIGHT, FOLIAR DRY WEIGHT, AND TOTAL NITROGEN CONTENT OF THE LEAVES OF TOMATO PLANTS* AFTER 12-DAYS OF FUMIGATION IN EXPERIMENT 2

	Treatment				
	A	B	C	D	E
Total nitrogen (%)	2.58a	2.64a	1.68b	1.89b	1.80b
Total dry weight (g)	9.4a	9.1a	3.8c	2.2c	5.9b
Total increase in height (cm)	20.9a	21.1a	6.0c	5.0c	16.6b

* Mean of 4 replicates.
All values in row followed by an a are greater than values followed by a b or c ($P<0.01$). Values followed by a b are greater than values followed by a c ($P<0.01$).

Experiment 3

The mean percent composition of the culture vessel atmospheres for each treatment is given in Table 44. The plants that were treated with low O_2 and low CO_2 (Treatment A) grew significantly better than the plants given high CO_2 with low O_2 or with high O_2 (Treatments B and C). This relationship was evidenced by dry weight of the leaf tissue, increased height of the plants and adventitious root development (Table 45). Five of the plants receiving high CO_2 (Treatments B and C) wilted after three days exposure, and all but two had recovered from their wilted condition by the fourth day of exposure. Of the two plants which did not recover, one was in Treatment B and one in Treatment C. By the tenth day of exposure all the plants given high CO_2 (Treatments B and C) exhibited adventitious root development on the shoots and a general chlorosis of the leaves. The plants remained in this condition throughout the experiment, exhibiting little additional growth. Adventitious root development was suppressed on the two plants which had wilted.

TABLE 44. MEAN PERCENT COMPOSITION* OF THE CULTURE VESSEL ATMOSPHERES IN EXPERIMENT 3

	Treatment		
Gas %	A	B	C
O_2	6.3	17.0	6.0
CO_2	0.3	28.7	28.8
N_2	93.4	54.3	65.2

* Corrected to 100 percent.

TABLE 45. TOTAL INCREASE IN HEIGHT, FOLIAR DRY WEIGHT AND ADVENTITIOUS ROOT DEVELOPMENT OF TOMATO PLANTS AT THE TERMINATION OF EXPERIMENT 3

	Treatment		
	A	B	C
Total increase in height (cm)	41.3a	2.4b	0.4b
Mean dry weight (g)	9.0a	3.0b	2.5b
Adventitious root development	-	+	+

* All values in row followed by an a are greater than values followed by a b ($P < 0.01$).

Experiment 4

The average composition of the atmospheres in the culture vessels for each treatment is given in Table 46.

The plants that were treated with low O_2 (control) or 10% CO_2 (Treatment A and B) grew significantly better than the plants treated with 20% CO_2 (Treatment C). The latter plants all exhibited adventitious root development and general chlorosis by the seventeenth day of exposure (Table 47). The adventitious root development involved, on the average, the lower 9.5 centimeters of the stem at the termination of the experiment. At the start of the experiment all the plants exhibited an interveinal chlorosis believed to have been caused by lack of light due to extended cloudy weather. By the tenth day of exposure this symptom had begun to subside on control and high CH_4 treated plants (Treatments A and D) but was more pronounced on the plants given 10 and 20% CO_2 (Treatments B and C). This symptom had disappeared from all plants by the seventeenth day of treatment but could have been masked on the plants receiving 20% CO_2 by the total chlorosis observed at this time.

By the seventeenth day of exposure all the plants receiving 50% CH_4 (Treatment D) exhibited adventitious root development involving the lower 28.5 centimeters or so of the stems at the termination of the experiment. These plants also exhibited chlorosis of the lower leaves and epinastic curvature of the lower one-third to one-half of the leaves, not all of which were exhibiting chlorosis. The development of these symptoms occurred concomitantly with the lowering of the O_2 percentage in the root atmospheres (Figure 25) presumably due to the activity of methane-utilizing microorganisms.

TABLE 46. MEAN PERCENT COMPOSITION* OF THE CULTURE VESSEL ATMOSPHERES IN EXPERIMENT 4

	Treatment			
Gas %	A	B	C	D
O_2	6.3	17.4	17.1	4.3
CO_2	0.4	9.1	18.0	1.7
N_2	93.3	73.5	64.9	49.6
CH_4	0.0	0.0	0.0	44.4

* Each value is the mean of 12 to 15 observations, corrected to 100 percent.

TABLE 47. TOTAL FOLIAR NITROGEN AND DRY WEIGHT AND INCREASE IN HEIGHT AND ADVENTITIOUS ROOT DEVELOPMENT OF TOMATO PLANTS* AT THE TERMINATION OF EXPERIMENT 4

	Treatment			
	A	B	C	D
Total nitrogen (%)	3.1a	2.5a	2.4a	2.0b
Mean total dry weight (g)	11.0a	9.5a	2.0b	8.5a
Total increase in height (cm)	41.0a	51.3a	3.8c	29.3b
Adventitious root development	-	-	+	+

* Mean of 4 replicates.
All values in a row followed by an a are greater than values followed by a b or c ($P < 0.01$). Values followed by a b are greater than values followed by a c ($P < 0.01$).

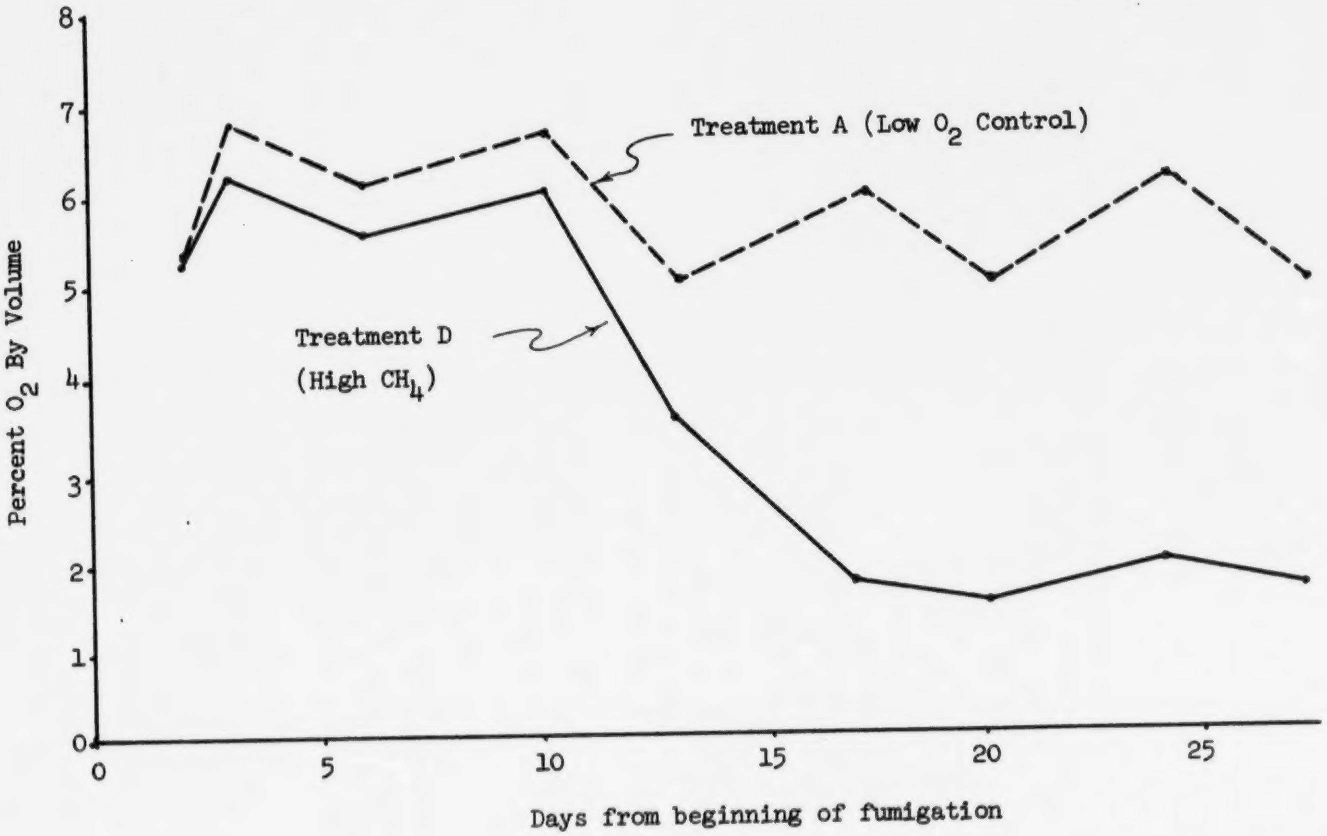


Figure 25. Percent oxygen in culture vessels in tomato Treatments A and D (Experiment 4).

SECTION 7

DISCUSSION

A survey of soil atmospheres on twenty completed sanitary landfills throughout the United States revealed that combustible gas (methane), CO_2 and, to a lesser degree, O_2 readings were concentrated in two extreme percentage categories rather than being evenly distributed among all of the categories (Tables 12, 13, and 14). The combustible gas readings were most extreme in this respect, with 86.2% of the samples containing less than 10% combustible gas by volume, whereas 12.3% of the samples contained 25% or more combustible gas and only 1.4% of the samples had combustible gas concentrations between 10 and 24.9%. This polarization of sample distribution is probably due to the tendency of refuse-generated gas to well up in specific areas rather than uniformly over the entire landfill site. This could be due to the fact that certain areas on the landfill are less restrictive of gas flow and act as chimneys for gas release, or to some characteristic of the refuse. This tendency of gas to occur in isolated areas in the cover material could be useful when vegetating these sites. By locating the areas where the gases are present, high concentrations can be avoided and the loss of expensive trees and shrubs can be minimized.

Data for soil gas composition on the Edgeboro Landfill indicated a strong correlation between the presence of landfill gases in the soil and the poor growth of existing vegetation. The gas samples were taken from a depth near or below the interface between the refuse and the cover material. This indicates that the presence or absence of landfill gases in the cover material was not a function of the depth of the cover but rather a function of the state of decomposition or some other characteristic of the refuse. The tendency of areas of soil covers saturated with landfill gases to be thinner than areas which did not contain landfill gases could be due to soil erosion brought about by lack of protective vegetation over the gas-saturated areas.

The Edgeboro data also indicate that severe contamination of the soil atmosphere by landfill gases was localized and stable on the undisturbed surface of the landfill during the fifteen month period of soil atmospheric-sampling. The large size of some of the existing trees in the areas containing little or no soil landfill gas indicates that these areas have probably been stable with respect to gas contamination for a number of years.

A considerable amount of effort and money could be saved when vegetating this or any former landfill where high concentrations of landfill gases are found to occur in the soil cover by not planting at these locations.

Most of the tree deaths on the Edgeboro experimental screening areas can be attributed to factors other than landfill gas (especially on the control). Low soil moisture, transplanting difficulties, animal damage and winter injury can explain many of the deaths.

Rhododendron suffered the greatest number of deaths all of which were attributable to lack of soil moisture or winter injury. Several of these on the experimental plot had landfill gas in the root zone, however, the gas was only detected after these rhododendrons had died. The demise of eight of the ten dead hybrid poplars can also be attributed to lack of soil moisture. These trees, six on the experimental and two on the control, had succumbed during the driest part of the summer of 1977 when the soil moisture reached 5.5% on the experimental plot and 6.0% on the control. No other species appeared to be as adversely affected by the low soil moisture as were these two.

Since black gum and sweet gum had been grown in containers in the nursery, their root systems were rather small at the time of planting, resulting in the death of several replicates of each species on the experimental plot due to lack of water. One replicate of each succumbed on the control plot, also from low soil moisture.

Damage to several euonymus trees by rabbits resulted in severe cambial disruption causing the death of five replicates on the experimental plot and poor growth of most of the others on the experimental and control plots.

The species which were very tall (12-15') at the time of planting (i.e. American sycamore, weeping willow and green ash) suffered from acute water deficiencies on the experimental plot apparently due to their large size. Many American sycamore and weeping willow trees died back and sprouted from the lower trunk and root collar during the first growing season (1976), whereas those on the control plot grew normally and suffered very little dieback.

Although landfill gas was not significantly correlated with death of trees, in a number of instances the carbon dioxide concentration at one foot beneath a recently dead Norway spruce was 18% and under a dead sweet gum 10%. On the other hand, landfill gases were consistently associated with death of trees in one landfill gas-barrier technique where carbon dioxide and methane were much higher than in the landfill screening area. Apparently, gas concentrations in most locations on the screening area were not high enough to cause tree death.

Although landfill gas concentrations in the experimental plot were not high enough to account for actual death of many of the plants, they were of adequate magnitude to detect the order of relative tolerance of the surviving trees as listed in Table 25. This listing resulted from a consideration of four tree variables including leaf and root biomass, shoot length (1976 and 1977) basal stem area.

It is interesting that of the nine most tolerant species, only three i.e. black gum, bayberry and pin oak, (73) have been reported to be able to withstand low oxygen tension in the soil, one of the criteria for selecting experimental species (Table 3). However, seven of these most tolerant species were three feet or less in height when planted, whereas seven of the last ten species in Table 25 were six feet or taller when planted. Obviously, the size of the tree as well as the biological ability of species to withstand low oxygen is important in selecting vegetation for completed sanitary landfills.

In order to assess the role of the various soil variables in predisposing these species to landfill tolerance, multiple regression analysis was performed for data from American basswood (the species present in both types of experiments) for the four tree variables (shoot length, leaf weight, root biomass, basal area). Results indicated that the soil variables, including oxygen, carbon dioxide, temperature, moisture content and bulk density explained a significant portion (95% C.L.) of the variability in the tree responses to landfill conditions. Examination of the quadratic effects of these variables did not result in an increase in the coefficients of determination (R^2); however, when the interactive and reciprocal effects were added to the models, the interactions: moisture content with carbon dioxide, and bulk density with carbon dioxide, as well as the reciprocal of carbon dioxide to the fourth power resulted in a significant increase in the coefficient of determination above that for the linear model.

Regression equations were computed for each of the four variables with respect to American basswood. The equation for shoot length (equation 2, page 84) indicates that the significant soil variables which explain 53% of the variability are carbon dioxide, temperature, bulk density, oxygen and moisture content. The negative coefficients for the first three soil variables indicate that high levels of these variables are correlated with a decrease in shoot length of American basswood trees while the positive coefficients for oxygen and moisture content correspond to an enhancement of growth at high levels and a detrimental effect at lower levels of oxygen and moisture content.

In that the reciprocal and interactive effects of the soil variables increased the R^2 value by 22% for leaf biomass, they were included in the final regression model for leaf biomass (see equation 4, page 85). The significant independent variables temperature, bulk density, the interaction of moisture content with carbon dioxide and the reciprocal of carbon dioxide to the fourth power explained 63% of the variability. High levels of all these variables correspond to a decrease in leaf biomass in that the regression coefficients are negative. The interaction of moisture content with carbon dioxide shows that for the same concentration of carbon dioxide, the leaf weight of basswood is different for different levels of moisture content. The reciprocal effect of carbon dioxide illustrates that at low carbon dioxide concentrations, a small increase in concentration corresponds to a large decrease in leaf weight, whereas at higher carbon dioxide levels, leaf weight changes very little with changes in carbon dioxide concentration.

Thirty-nine percent of the variability in root biomass can be attributed to the soil variables temperature, bulk density and moisture content leaving a considerable amount of the variability unexplained. In that the variance in the root biomass among basswood trees is large compared to the variance among the screening areas and the gas-barrier techniques, it is not surprising that only a small portion of the variability could be accounted for by the independent soil variables. The large variance among trees can be partially explained by the sampling method. The method of sampling roots for the present study, i.e. taking only one sample per tree, is subject to a large amount of error in that the likelihood of collecting widely different biomass for trees growing under the same conditions is high. This stems from the fact that one sample collected from a particular tree may have purely by chance, been taken from a portion of the root system high in root biomass while a sample from another tree may have come from an area of low biomass. This problem can be partially overcome by sampling roots from two or more areas around a particular tree.

The significant effects in the equation describing the basal stem cross-sectional area response of American basswood, with an R^2 of fifty-three percent, were bulk density, the interaction of bulk density with carbon dioxide, and the reciprocal of carbon dioxide to the fourth power. Since the regression coefficient for each of these effects was negative, an increase in the value for these significant soil variables corresponds to a decrease in the basal area. The significant interaction effect illustrates that at a particular level of carbon dioxide, the difference in basal area is not the same for different levels of bulk density. The significant reciprocal effect for carbon diocide shows that a low CO_2 concentration (i.e. 0-5%), a small increase in concentration results in a large decrease in the basal area, whereas at higher concentration (i.e. 5-30% CO_2), an increase in carbon dioxide corresponds with a small decrease in basal area. Rajappan (120) has shown that root growth of red kidney bean was completely inhibited at carbon dioxide concentrations of 5.5%. On the other hand, cotton seedlings grown in hydroponic solution were able to make optimum growth with 10% carbon dioxide present, provided at least 7.5% oxygen was present (52).

Apparently, the variability within each basswood tree for shoot length and leaf weight has been provided for adequately by collecting six and four measurements per tree respectively, because the variance of these two variables for a particular tree is small compared with the variance among trees. Consequently, the R^2 values for shoot length (53%) and leaf weight (63%) are considerably higher than that for root biomass (39%) where one sample per tree was collected.

In that there is only one measurement possible for the cross-sectional basal area of a particular tree, its value should represent very well the amount of growth which that particular tree has produced. However, since the calculation of cross section basal area is dependent upon the tree diameter, then any error in the diameter measurement would result in an erroneous basal area. Furthermore, when the diameter measurement is used for the calculation of basal area, a circular cross section is assumed. This is indeed an invalid assumption in that several of the trees are obviously not circular. Despite the high R^2 value (53%) for basal area of American basswood, some of the unexplained variability can most likely be attributed to the non-circularity of some of the trees.

Despite the correlation of carbon dioxide with the growth of American basswood, higher R^2 values may be obtainable by placing the soil gas collection samplers at a depth comparable to the depth of the root system. This depth was found to be approximately six inches on the experimental plot and eight inches on the control plot. For the present study, gas samplers were twelve inches below the soil surface. Since the average root depth was four to six inches above the depth of the samplers, the gas concentration in the root zone was not precisely measured. However, since carbon dioxide correlates so well with poor growth, apparently the carbon dioxide at twelve inches was related to the concentration in which the roots were growing.

Until now, oxygen has not been considered in the discussion of soil factors and their effect on tree growth since oxygen became a significant effect in only one of the four descriptive equations. The values for oxygen correlated very highly ($r = -.938$) with those for carbon dioxide. Since carbon dioxide was slightly better correlated with growth than oxygen, it was entered into the majority of the equations and oxygen was omitted. However, the absence of oxygen in the equation describing the variability in growth must be interpreted with care. Since it is impossible to describe the effects of each of these gases separately any discussion of the effects of high carbon dioxide concentration on growth is confounded with the effects of low oxygen.

Methane gas concentrations on the experimental plot screening area averaged approximately one percent of the soil gas atmosphere at a depth of one foot. Since this concentration is low, methane was not a significant factor in explaining the variability in the tree responses. The low methane concentration may be due to the action of Pseudomonas chromobacterium in the landfill cover soil which utilizes methane as a source of carbon in its metabolism (70). Oxygen is also required during the metabolism of these bacteria which ultimately produce carbon dioxide and release it to the surrounding soil. Therefore, the action of these bacteria in the landfill cover-soil results in the production of carbon dioxide at the expense of oxygen and methane. This reaction may be significant in that our studies indicate that methane is innocuous to tomato plants if oxygen is not limiting, whereas carbon dioxide has a detrimental effect on growth. If activity of these bacteria can be inhibited, then less carbon dioxide will be present in the landfill soil and the vegetation growing in this soil may have a better chance to survive.

The nature of the soil strata (i.e. consisting of ten year old refuse lying beneath two feet of soil) and perhaps the higher soil temperatures and sand content on the experimental landfill plot helped promote drying of the soil. Normal capillary water movement is restricted in such a soil structure to the top two-feet enabling the roots to obtain additional water only from irrigation or rainfall, and not from deeper soil layers. The soil structure on the control plot is closer to normal with two feet of soil spread over virgin land. Here, capillary action can help supply water to the roots under low moisture conditions. In addition, the slope of the experimental plot was about two percent whereas that of the control was one percent, promoting more runoff on the experimental plot and resulting in less water percolation and ultimately a lower soil moisture content. If the rate of transpiration is measured on both plots for particular species along with soil moisture content through time, rate of soil moisture loss relative to the transpiration rate can be calculated for both plots. If these rates are proportional on the control plot and not proportional on the experimental plot, then some of the water was perhaps lost from the experimental plot soil by processes other than transpiration.

This could imply one of two processes: first, that more water is percolating through the two-foot soil layer on the experimental plot and being lost to the refuse layer below and that on the control plot the undisturbed soil beneath the top two feet is slowing down percolation; second, that on the control plot, the deeper soil permits capillary water movement upwards toward the dryer surface layer where the roots are located and that on the experimental plot where only two feet of soil lies above thirty feet of refuse, these deeper soil layers are not present to facilitate such capillary action. Further studies may show whether or not these relationships are valid.

The trees on the control plot produced more leaf biomass than those on the experimental plot, causing more of the smaller trees and shrubs as well as the soil to be shaded to a greater extent on the control plot. This may have tended to reduce the transpiration rate of the shaded plants and thus the rate of evaporation from the soil surface to lessen the water demand on the control plot. In that soil moisture content has contributed significantly to explaining the variability in equations two (page 84) and five (page 85) let us examine it further.

The experimental plot was also more exposed to the elements and more likely to be subjected to stronger winds than the control. This could place an even greater demand for water on the trees growing in the experimental plot so that the evapotranspiration rate would be enhanced at the expense of soil moisture and may further explain the significantly lower soil moisture on the experimental plot.

The direct relationship of soil moisture content with plant response is brought out by the positive regression coefficients for moisture content in equations two and five showing that when moisture content was increased, the American basswood trees responded by increasing growth. Although this relationship is significant when all the American basswood data is included in the analysis, where moisture content was highest (in clay/vents trench), the growth of basswood was the poorest, i.e. the reverse of the previously stated relationship. This supports the positive relationship between growth and soil moisture content in that the regression coefficient is positive, despite the reverse relationship in the clay/vents trench.

Why then is the high moisture content in the clay/vents trench associated with the poorest growth? To answer this question it is necessary to recall that water is one of the products of decomposition of the organic matter in refuse (21). In addition it is also produced by the methane-utilizing bacteria (70). It travels along with the other decompositional gases and since both carbon dioxide and methane were high in this trench, presumably the high moisture content resulted from water vapor migrating with these decomposition gases. The carbon dioxide concentration was a significant factor in the regression equation calculated for shoot length, leaf weight and basal area for American basswood and had a negative coefficient, illustrating the detrimental effect of carbon dioxide on American basswood growth. Therefore, the high carbon dioxide in the clay/vents trench appeared to have contributed largely to the poor growth of these trees despite the high moisture content.

Lack of soil moisture might have had an effect not only in reducing water uptake by plants on the experimental plot and ultimately reducing productivity, but also by reducing the assimilation of very soluble nutrients such as nitrogen. Although the leaf tissue was not analyzed for nutrient content during the present study, future analysis will make possible a better understanding of the effects of landfill soil environment on nutrient uptake and assimilation.

The soil nutrient levels were also found to be influenced by the landfill environment. The ratio of $NO_3^-:NH_4^+$ on the experimental and control screening areas were identical following the application of fertilizer in the spring of 1977; however, by November of 1977, the $NO_3^-:NH_4^+$ ratio on the control was more than two times greater and significantly different from the ratio on the experimental plot indicating one or both of two things: either more ammonium nitrogen was converted to nitrate on the control plot because of the higher oxygen concentration in the soil on the control plot, or nitrate on the experimental plot was reduced to ammonium due to the utilization of the oxygen portion of nitrate in the metabolism of soil bacteria (117). This reduced the amount of nitrate in the soil and could result in a lower $NO_3^-:NH_4^+$ ratio as exhibited on the experimental plot.

The $NO_3^-:NH_4^+$ ratio in the clay/vents trench where the oxygen concentration was 4.3%, was more than two times less than the other gas-barrier techniques where the oxygen was 16.3% or greater. The same two possibilities as described above most probably contributed to these phenomena.

The manganese content in the experimental and control screening areas as well as in six of the seven gas-barrier techniques averaged approximately 10 ppm. However, in the clay/vents trench, where the oxygen concentration averaged 4.3%, the manganese reached 45 ppm. These relationships indicated that at oxygen concentrations of 17.8% (i.e. on the experimental screening area), free manganese does not increase in the soil. However, when the average oxygen concentration is 4.3% (i.e. in the clay/vents trench) then manganese is significantly increased in the soil. Manganese available to plants is reportedly significantly increased in soils flooded for short periods of time (117).

Considering the nutrient changes described above, it is apparent that at oxygen concentration of 17.8% on the experimental plot, a slight reduction in the ratio of nitrate to ammonium nitrogen is occurring (Table 8) compared to the control where the oxygen concentration is 19.7% and that when the oxygen concentration reaches 4.3% (in clay/vents trench), oxides of manganese are also reduced, increasing the free manganese in the soil (Table 33).

Because the pH of the soil in the clay/vents trench was very low

(5.0) the high manganese content may have been toxic to the plants in the trench and contributed to their demise. One recommendation to help lower the availability of manganese is to lime the soil, thereby raising the pH and decreasing the likelihood of manganese toxicity to plants.

The effectiveness of each gas-barrier technique in preventing methane gas migration into the trenches may be evaluated by considering the ratio between the methane concentrations around the periphery of the trench and those inside the trench. In the gravel/plastic/vents trench and clay barrier trench, the ratios are 207:1 and 54:1 respectively, indicating that these trenches have functioned effectively in keeping out methane gas. On the other hand, for the clay/vents trench, the 1:1 ratio indicated that this gas-barrier technique was not effective in preventing the migration of methane from the refuse into the trench.

No gas measurements were made in the soil immediately adjacent to either of the two mounds on the experimental plot. However, methane or elevated carbon dioxide levels were never detected in either mound. Furthermore, the average carbon dioxide concentration on the experimental screening area surrounding these mounds was six percent indicating that both mounds functioned successfully in preventing gas migration.

Interpreting the effectiveness of each gas-barrier technique is not as straightforward as it may first appear. Despite the previously presented ratios between gas outside and gas inside the trenches, the concentrations below the trenches were not measured and may differ from one trench to another. In addition there is no way to determine if the clay barrier below the clay/vents trench has remained intact. Although there are not obvious signs of refuse settlement around this trench, small amounts of settlement may have split the clay barrier allowing the upward movement of gases into the soil in the trench. This might explain the high methane and carbon dioxide in this trench. Future experiments with gas-barrier techniques should include more than one application of each technique in order to make adequate assessment of effectiveness in preventing gas migration. In this study only one replicate of each technique was employed.

Another way of assessing the effectiveness of each barrier technique was by the growth of the two species in each of these areas. For the same three techniques which prevented landfill gas from contaminating the soil, analysis of variance showed growth of American basswood significantly greater (99% C.L.) than the experimental screening area which acted as the control for the barrier techniques. Because of the large variability in growth responses of Japanese yew within each technique no significant differences were found between the techniques and the experimental screening area for this species. Presumably, the great variability in Japanese yew growth was partially due to planting only four replicates per technique instead of six as were planted for American basswood.

Carbon dioxide contamination in the root zone of tomato plants in solution culture was toxic when the concentration of CO_2 averaged 17.0% during the experimental period. When CO_2 concentrations averaged 8.8% or less no symptoms were observed, indicating that there was a threshold level between

9 and 17% at which CO_2 became toxic under these experimental conditions. Tomato plants exposed to 17% CO_2 exhibited progressive chlorosis and abscission of the lower leaves, adventitious root development, swelling of the stem near the nodes, chlorosis of the entire plant, and a reduction in the growth rate. Complete symptom development was observed on all plants by the 17th day of fumigation. Exposing tomato roots to concentrations of CO_2 between 25 and 36% resulted in earlier and more severe symptom development on tomato plants than did 17% CO_2. These higher CO_2 concentrations caused some of the plants to wilt after only three days of fumigation, and some plants never recovered. The other symptoms were fully expressed on all plants given 26 to 27% CO_2 by the tenth day of fumigation and on plants given 34 to 38% CO_2 by the eighth day of fumigation.

These findings are consistent with what is reported in the literature. Erickson (44) in 1946 found that 28% CO_2 in the root zone severely reduced the growth rate of tomato plants. The symptom development observed in this experiment was also similar to that observed by Erickson on plants exposed to low O_2 and/or high CO_2 in the root medium. This type of symptom development was also reported by Jackson (75) in 1948 and Kramer (84) in 1951, on tomato plants grown in poorly aerated growth media.

No interaction was observed among O_2, CO_2 and CH_4 when they occurred together in the root zone in terms of symptom development on tomato plants. When the CO_2 was held at 27%, O_2 at either 5.5 or 16% caused no differences in symptom development. Plants exposed to 34 to 38% CO_2 alone exhibited the same symptom development as plants exposed to 34 to 38% CO_2 with 43% CH_4.

Exposing the roots of tomato plants to 43% CH_4 for an 8-day period resulted in no measurable adverse effects, whereas a 12-day exposure resulted in a decline of the tomato plants concomitant with a decrease in O_2 concentration in the culture vessels. This decrease in O_2 is believed to be due to the activity of methane-utilizing microorganisms. Hoeks (70) in 1970 also reported that exposing soil to high concentrations of CH_4 resulted in eutrophication by the second week of exposure.

Tomato plants are known to be sensitive to poor soil aeration and will exhibit characteristic symptoms when so exposed (44, 75, 84). These symptoms include: adventitious root development, swelling of the stem near the nodes, progressive chlorosis and abscission of the lower leaves, reduction in growth and an epinastic curvature of the leaf petioles. Such symptoms were duplicated exactly when the O_2 concentrations decreased in the cultures fumigated with 43% CH_4. However, the plants exposed to high concentrations of CO_2 exhibited less extensive adventitious root development, less swelling of the stem and little or no epinastic curvature. Chlorosis often involved the entire plant rather than just the lower leaves, and in some cases the entire plant wilted after only a few days of exposure. This indicates that CO_2 may damage tomato plants by means of a mechanism different from that through which low O_2 concentrations in the root zone causes plant damage.

Sugar maple was intolerant of flooding as evidenced by the statistically significant decrease in transpiration rate after only one day of flooding and the loss of all leaves by the termination of the experiment. Red maple seedlings were more tolerant of flooding than were more tolerant of flooding than were sugar maples, their transpiration rate did not decrease until the 42nd day of flooding and this decrease was not statistically significant. The lower half of the leaves on the flooded red maples were chlorotic by the end of the experiment but this did not influence the stomatal diffusion because the porometer readings were taken only on the uppermost leaves. The fact that red maple is more tolerant of flooding than sugar maple has been reported in the literature (61).

Flood tolerance has been attributed to more than one adaptive mechanism in several species (72). The adventitious root development and swelling of lenticels observed on the flooded red maples in this experiment have been found to occur on many other "flood tolerant" species and are believed to contribute to flood tolerance to some degree. Such morphological adaptations were not observed on the red maples fumigated with simulated sanitary landfill gas mixtures. This is not surprising since adventitious root development is dependent upon the presence of water and lenticel opening requires high humidity near the stem. Other adaptations which are believed to contribute to flood tolerance which are not as water dependent include the ability to withstand elevated levels of CO_2 in the soil (72) and to undergo anaerobic root respiration without the production of inhibitory concentrations of ethanol. Mechanisms such as these could explain why the differences between the two species were more pronounced in their response to flooding than to soil contamination with simulated landfill gas. The inability to develop adventitious roots and to permit opening of the lenticels in response to landfill gas contamination would reduce the advantage enjoyed by flood tolerant species, whereas, other mechanisms contributing to flood tolerance such as the ability to withstand elevated levels of CO_2 in the soil or undergo anaerobic respiration in the roots which are not inhibited by lack of water and would continue to supply some protection.

Considering these factors, red maple might be a better choice as a tree to plant on a completed sanitary landfill than sugar maple. The ability to withstand flooding might be a good characteristic for a tree to have since uneven settlement of the refuse can wreak havoc with surface drainage, creating ephemeral ponds. The greater ability of red maple than sugar maple to withstand the presence of CO_2 and CH_4 in the soil was not as dramatic as the ability to withstand flooding. Being less sensitive to these gases red maple could develop a more extensive root system giving it a competitive advantage over sugar maple whose root development would be more likely to be inhibited by high CO_2 and CH_4 in the soil.

SECTION 8

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